UNIVERSITÀ DEGLI STUDI DI MILANO

INFN Istituto Nazionale di Fisica Nucleare

EW tools for the high-precision description of Drell-Yan final states at hadron colliders

Alessandro Vicini

University of Milano, INFN Milano

Brookhaven, April 4th 2013

Motivations

- tests of the Standard Model after the discovery of a Higgs boson candidate at the quantum level
  search for tensions that might point to a BSM signal

- precision measurement of MW and of sin2thetaW

- measurement of differential cross sections and of asymmetries in Drell-Yan processes

Plan of the talk

- combined QCD+EW corrections to Drell-Yan in POWHEG, CC and NC channels

- accurate description of the gauge boson transverse momentum distribution

Leitmotiv

- a unique tool which incorporates all the desirable features to describe any possible observable
  does not exist yet

→ for each observable we must discuss the main problems and the corresponding available solutions

From differential cross sections and asymmetries to masses and couplings

CC-DY: lepton-pair transverse mass
lepton transverse momentum

$M_W\,,\Gamma_W$ from study of the jacobian peak

→ control of the lineshape at the per mille level

NC-DY: lepton-pair invariant mass

$M_Z\,,\Gamma_Z$ from measurement of the resonance

CC/NC: rapidity and pseudo-rapidity

total cross section
PDF determination

→ requires precise determination of detector acceptance

NC: invariant mass A_FB asymmetry

$\sin^2\theta_W$ possible thanks to the PDF unbalance in forward (backward) region between qqbar and qbarq initiated processes

to appreciate the impact of the radiative corrections

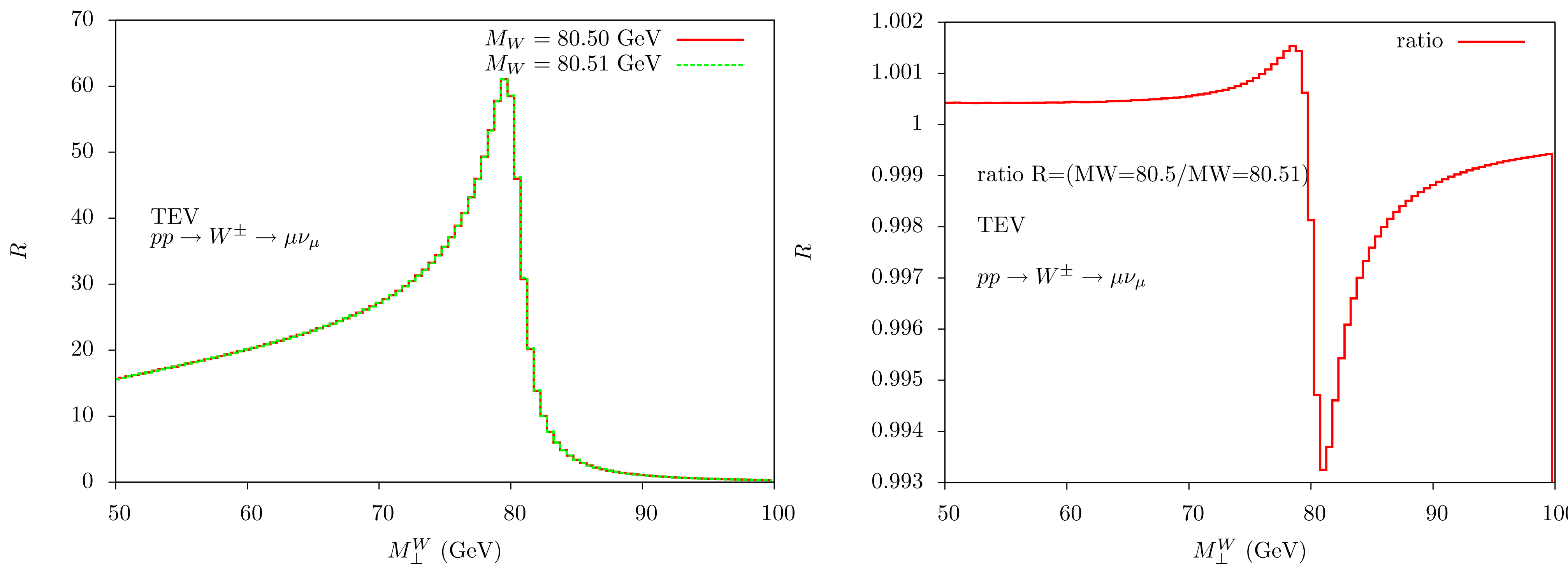
- discuss individual observables (inclusive *vs* exclusive)
- universal and process dependent corrections

Template fit and theoretical accuracy

In a template fit approach

- the best theoretical prediction for a distribution is computed several times, with different values of MW
- each template is compared to the data
- the measured MW is the one of the template that maximizes the agreement with the data

Which level of accuracy do we need?



If we aim at measuring MW with 10-15 MeV of error, are we able to control the shape of the distributions and the theoretical uncertainties at the few per mille level?

Not all the radiative corrections have the same impact on the MW measurement
not all the uncertainties are equally bad on the final error

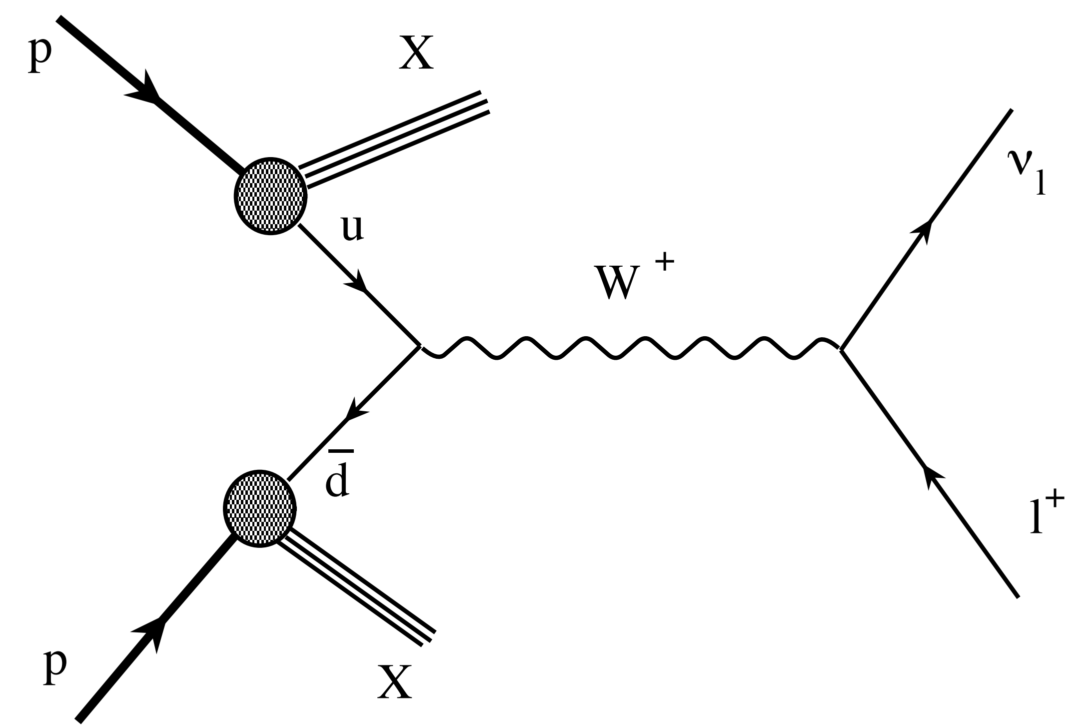
Perturbative expansion of the Drell-Yan cross section

$$\begin{aligned}\sigma_{tot} &= \sigma_0 + \boxed{\alpha_s\sigma_{\alpha_s} + \alpha_s^2\sigma_{\alpha_s^2} + \ldots} \\ &+ \boxed{\alpha\sigma_\alpha + \alpha^2\sigma_{\alpha^2} + \ldots} \\ &+ \boxed{\alpha\alpha_s\ \sigma_{\alpha\alpha_s} + \alpha\alpha_s^2\ \sigma_{\alpha\alpha_s^2} + \ldots}\end{aligned}$$

QCD

EW

mixed QCDxEW



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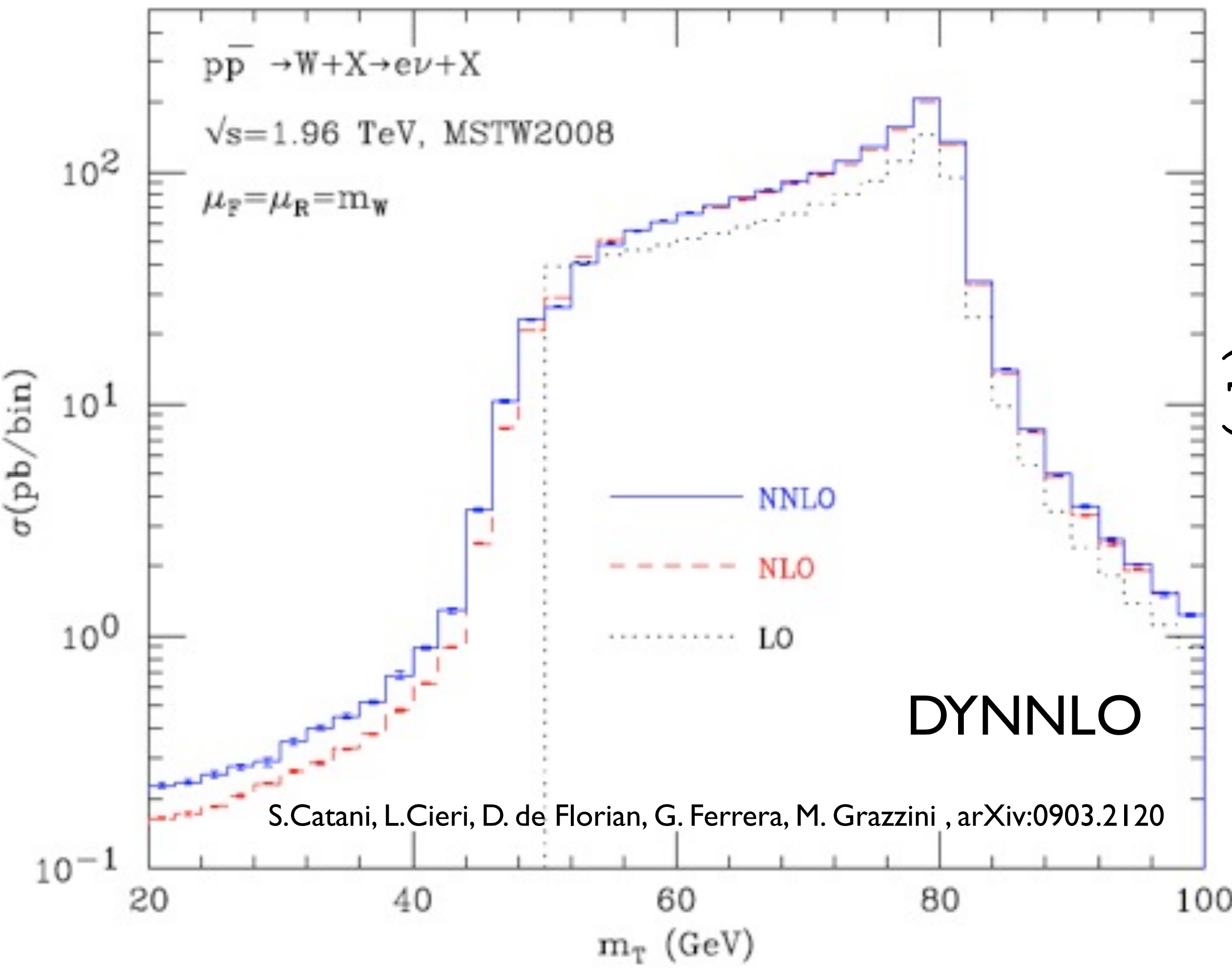
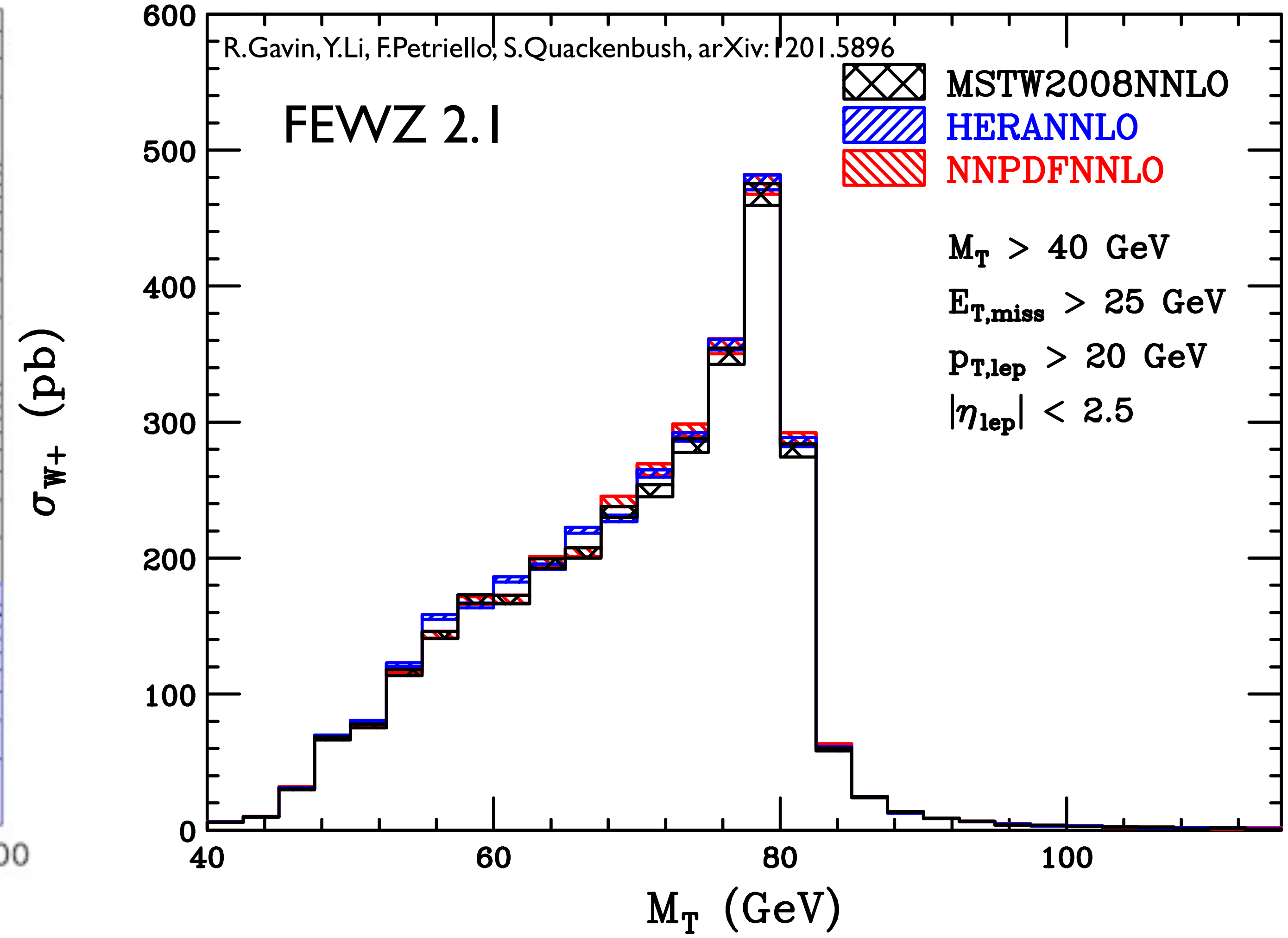
$$+ \boxed{\alpha \sigma_\alpha} + \alpha^2 \sigma_{\alpha^2} + \ldots$$
$$+ \alpha \alpha_s \, \sigma_{\alpha\alpha_s} + \alpha\alpha_s^2 \, \sigma_{\alpha\alpha_s^2} + \ldots$$

MCFM,FEWZ,DYNNLO

Fixed order corrections exactly evaluated and available in simulation codes





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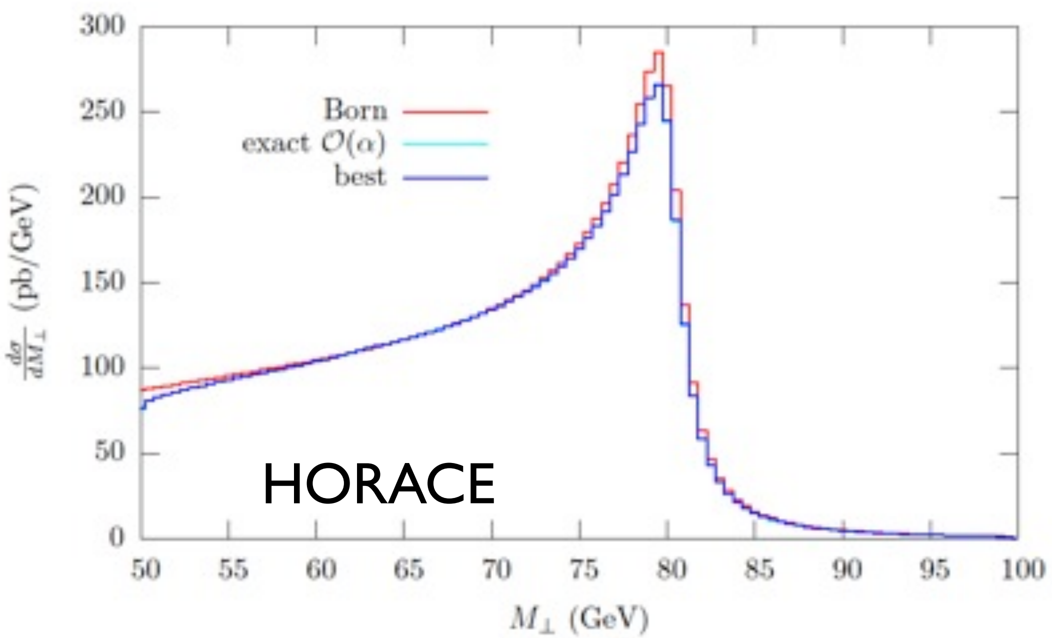
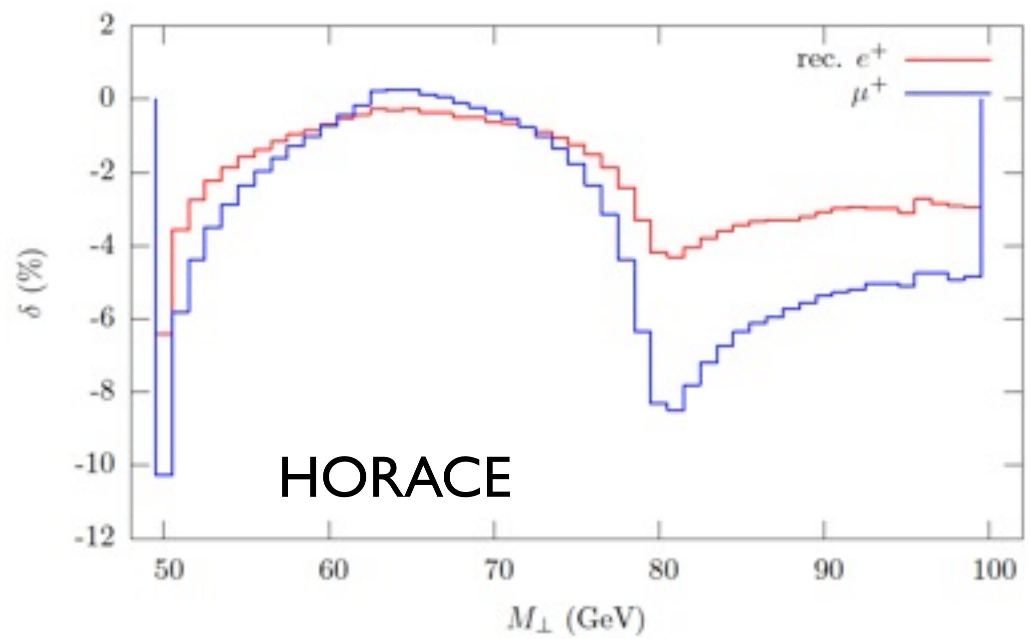
WGRAD, RADY, HORACE, SANC

Fixed order corrections exactly evaluated and available in simulation codes





The change of the final state lepton distribution yields a huge shift in the extracted MW value

$$\Delta M_W^\alpha = 110 \text{ MeV}$$

Perturbative expansion of the Drell-Yan cross section

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Fixed order corrections exactly evaluated and available in simulation codes

Subsets of corrections partially evaluated or approximated

$O(\alpha^2)$

- EW Sudakov logs J.Kühn, A.Kulesza, S.Pozzorini, M.Schulze, Nucl.Phys.B797:27-77,2008, Phys.Lett.B651:160-165,2007, Nucl.Phys.B727:368-394,2005.
- QED LL
- QED NLL (approximated)
- additional light pairs (approximated)

$O(\alpha\alpha_s)$

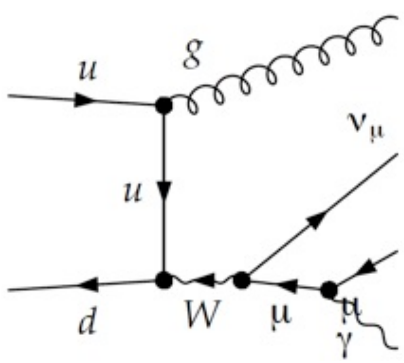
- EW corrections to ffbar+jet production
- QCD corrections to ffbar+gamma production

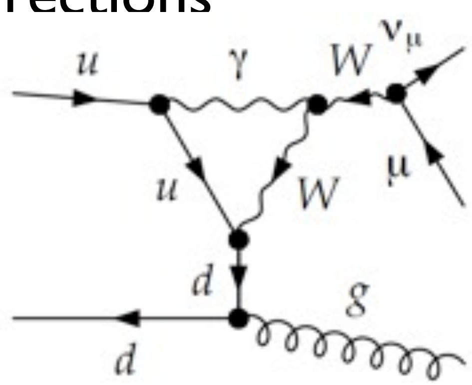
A.Denner, S.Dittmaier, T.Kasprzik, A.Mueck, arXiv:0909.3943, arXiv:1103.0914

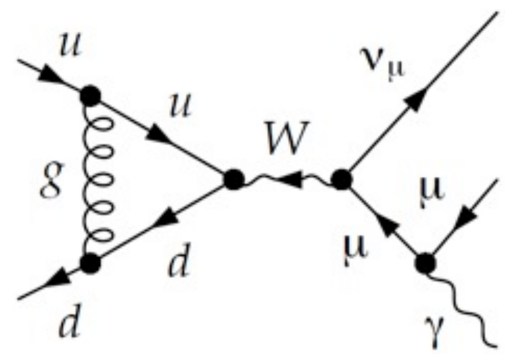
Mixed QCDxEW corrections the Drell-Yan cross section

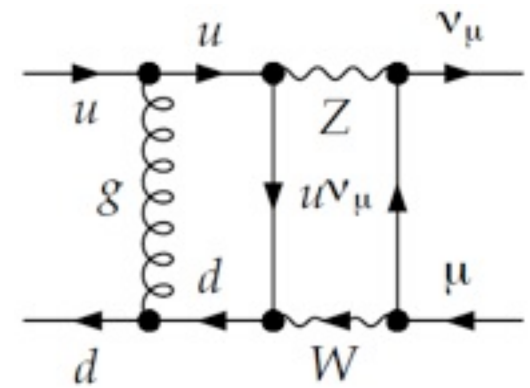
$$\begin{aligned}\sigma_{tot} &= \sigma_0 + \alpha_s\sigma_{\alpha_s} + \alpha_s^2\sigma_{\alpha_s^2} + \ldots \\ &+ \alpha\sigma_\alpha + \alpha^2\sigma_{\alpha^2} + \ldots \\ &+ \boxed{\alpha\alpha_s\, \sigma_{\alpha\alpha_s}} + \alpha\alpha_s^2\, \sigma_{\alpha\alpha_s^2} + \ldots\end{aligned}$$

- The first mixed QCDxEW corrections include different contributions:
  - emission of two real additional partons (one photon + one gluon/quark)
  - emission of one real additional parton (one photon with QCD virtual corrections, one gluon/quark with EW virtual corrections)
  - two-loop virtual corrections







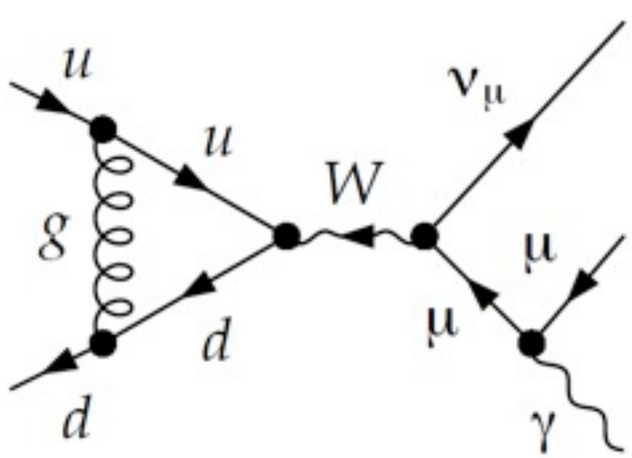


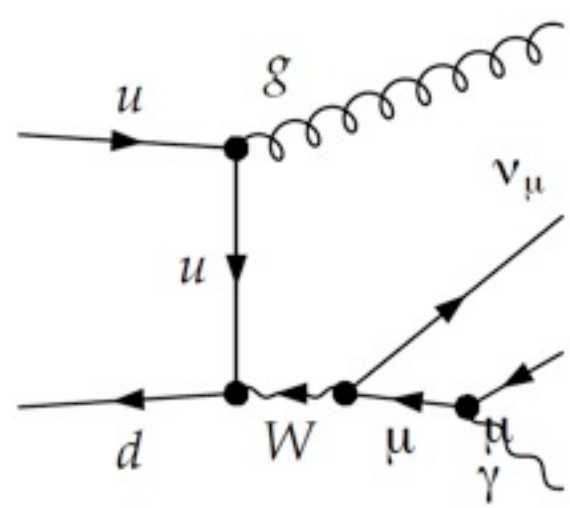
- an exact complete calculation is not yet available, neither for DY nor for single gauge boson production

W.B. Kilgore, C. Sturm, arXiv:1107.4798

- The bulk of the mixed QCDxEW corrections, relevant for a precision MW measurement, is factorized in QCD and EW contributions:

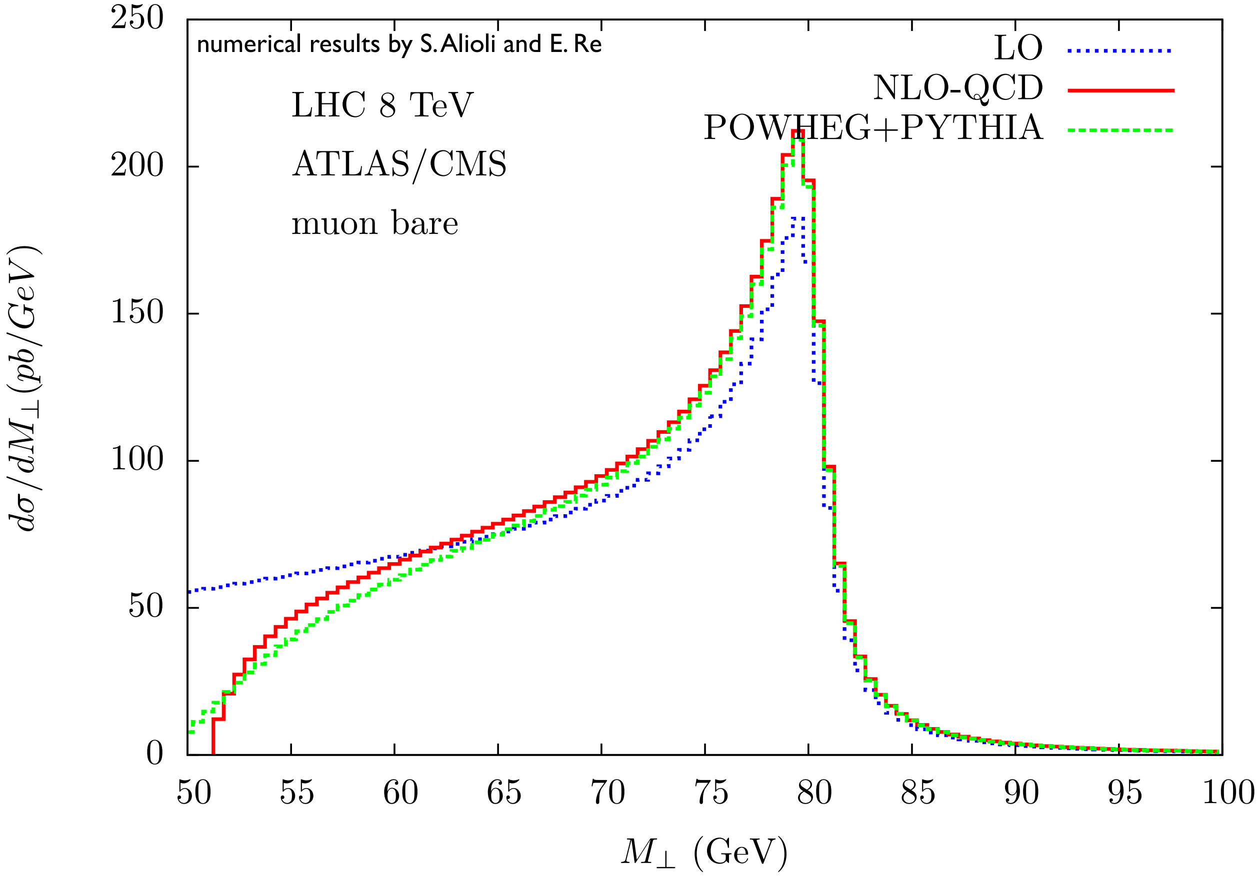
(leading-log part of final state QED radiation) X (leading-log part of initial state QCD radiation || NLO-QCD contribution to the K-factor)





In any case, a fixed order description of the process is not sufficient...

Inclusive *vs* exclusive observables: pure QCD comparison



numerical results by S. Alioli and E. Re

- NLO-QCD corrections over LO predictions are quite flat
- resummation of multiple-gluon emissions has tiny impact

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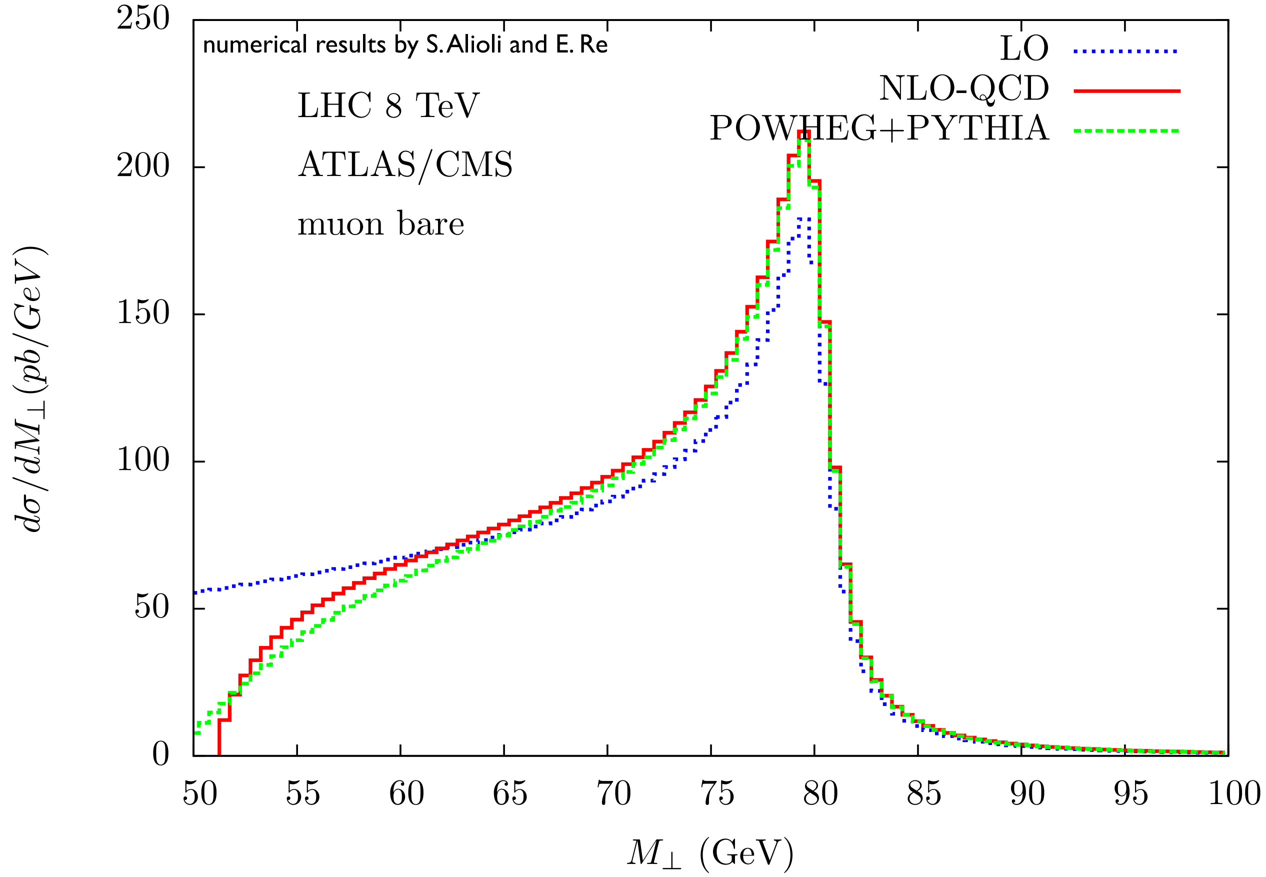

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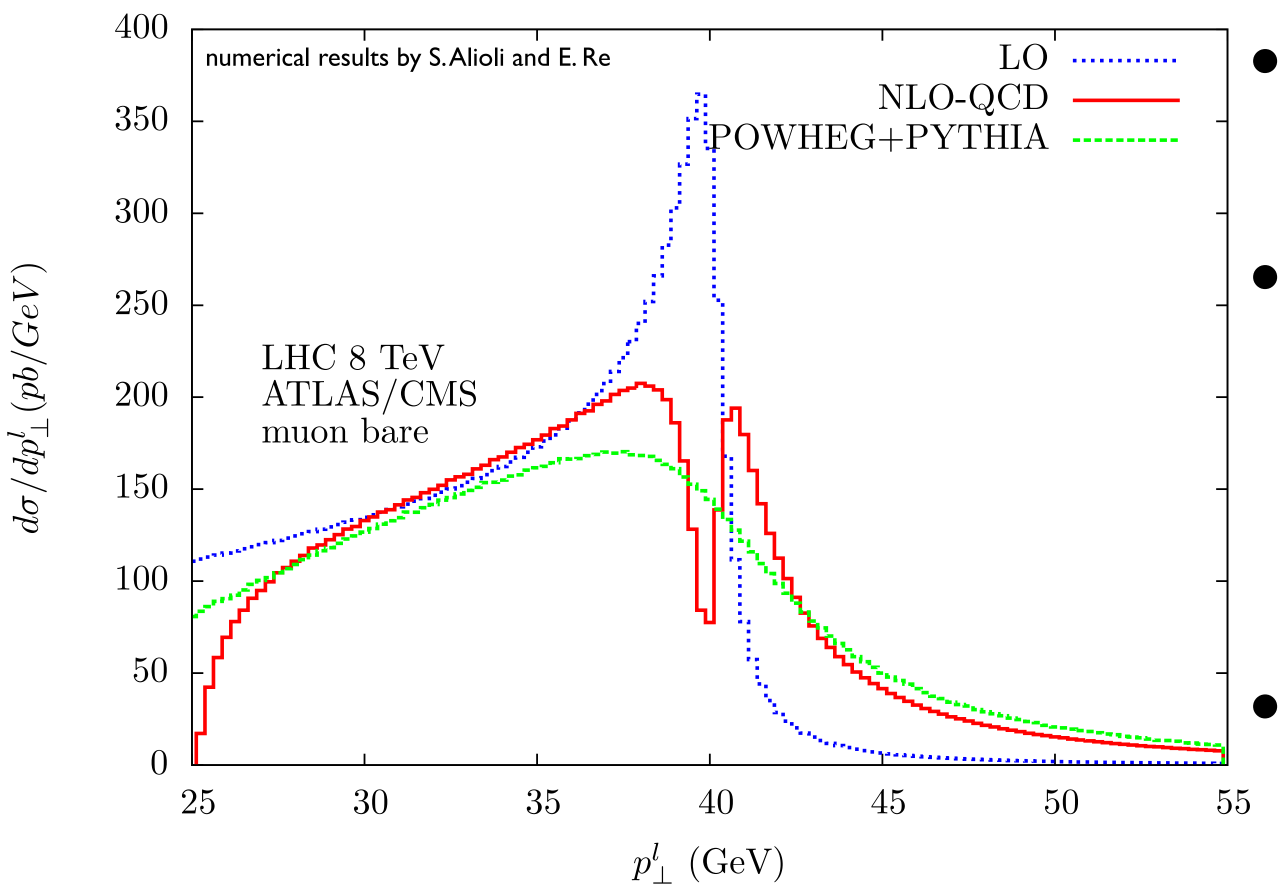


- at LO only the W decay generates the lepton pt with Gamma_W smearing effect in the right tail
- at NLO-QCD the lepton pt receives contributions from
  - the W recoil against QCD radiation (singular at ptW→0)
    → need to resum multiple-gluon emissions
  - the subprocess qg→qlν
- matching NLO-QCD with Parton Shower smears the distribution
  → sensitivity to the resummation details

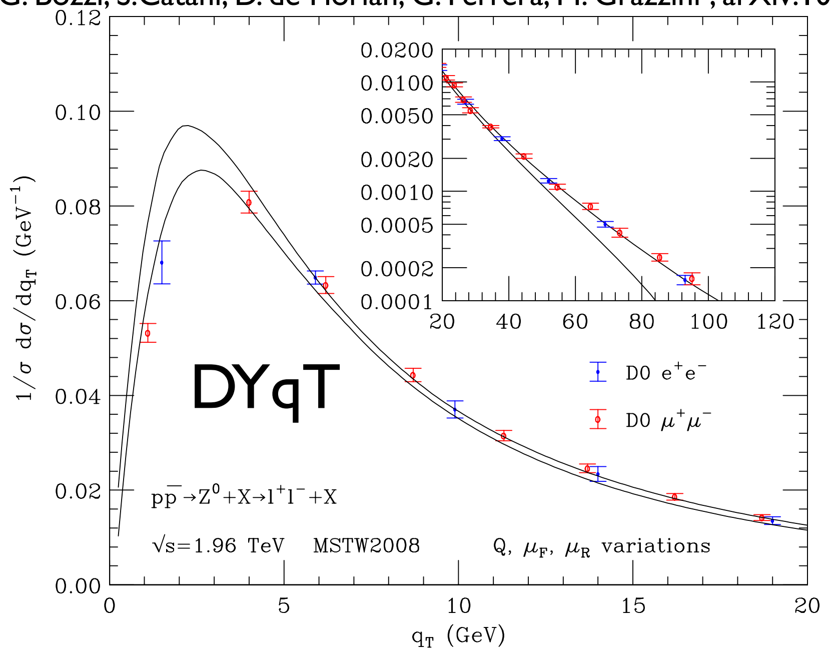
The relevance of multiple gluon/photon emission

numerical simulation of IS QCD multiple gluon emission via Parton Shower (Herwig, Pythia, Sherpa)

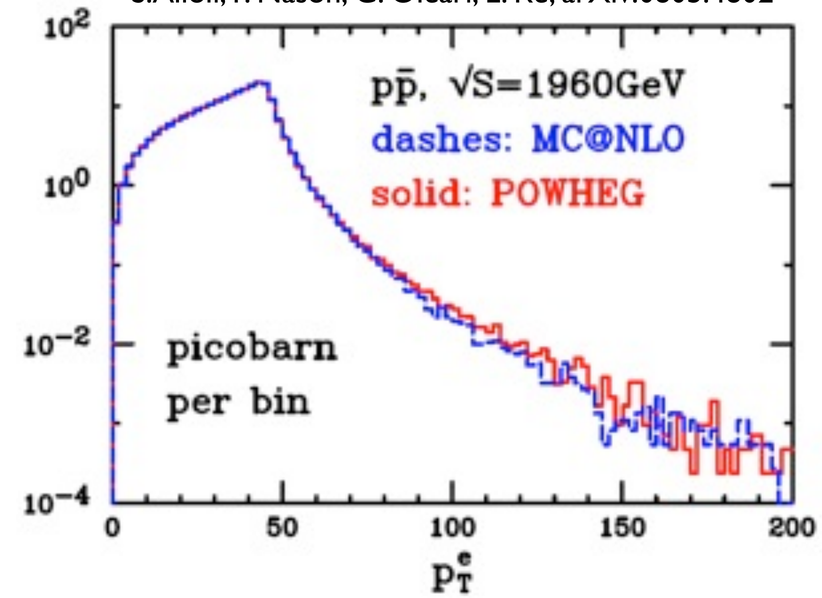
matching of NLO-QCD results with QCD Parton Shower (MC@NLO, POWHEG)

analytical resummation of initial state QCD multiple gluon emission (Resbos, DYqT)

G. Bozzi, S.Catani, D. de Florian, G. Ferrera, M. Grazzini , arXiv:1007.2351



S.Alioli, P. Nason, C. Oleari, E. Re, arXiv:0805.4802



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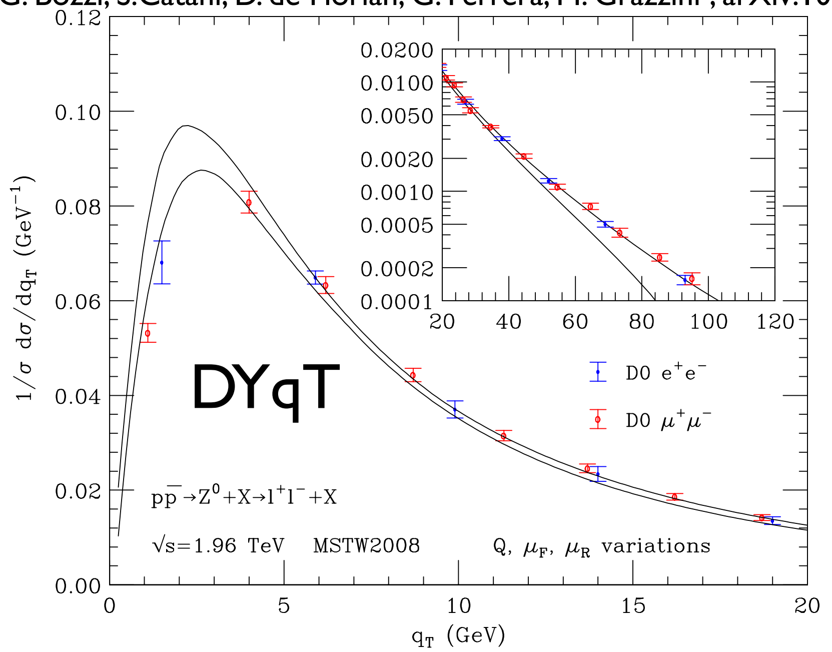

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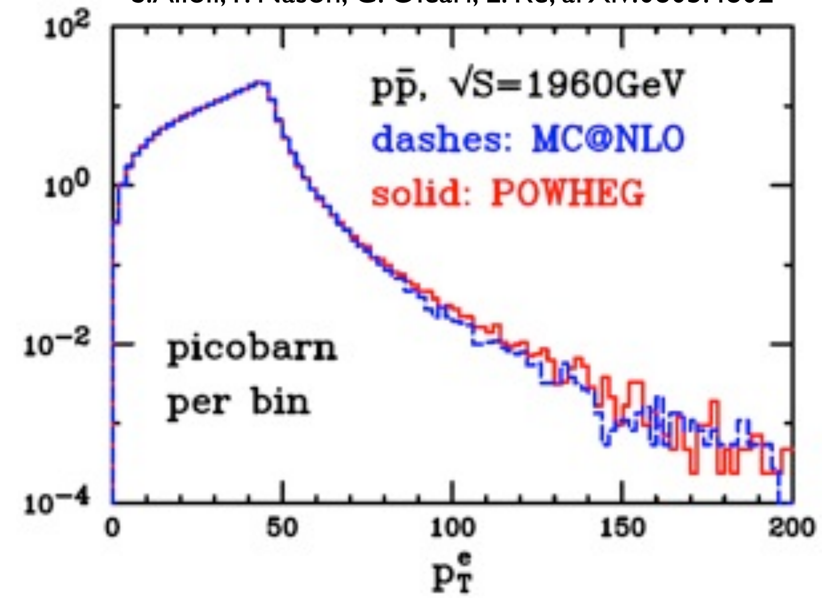
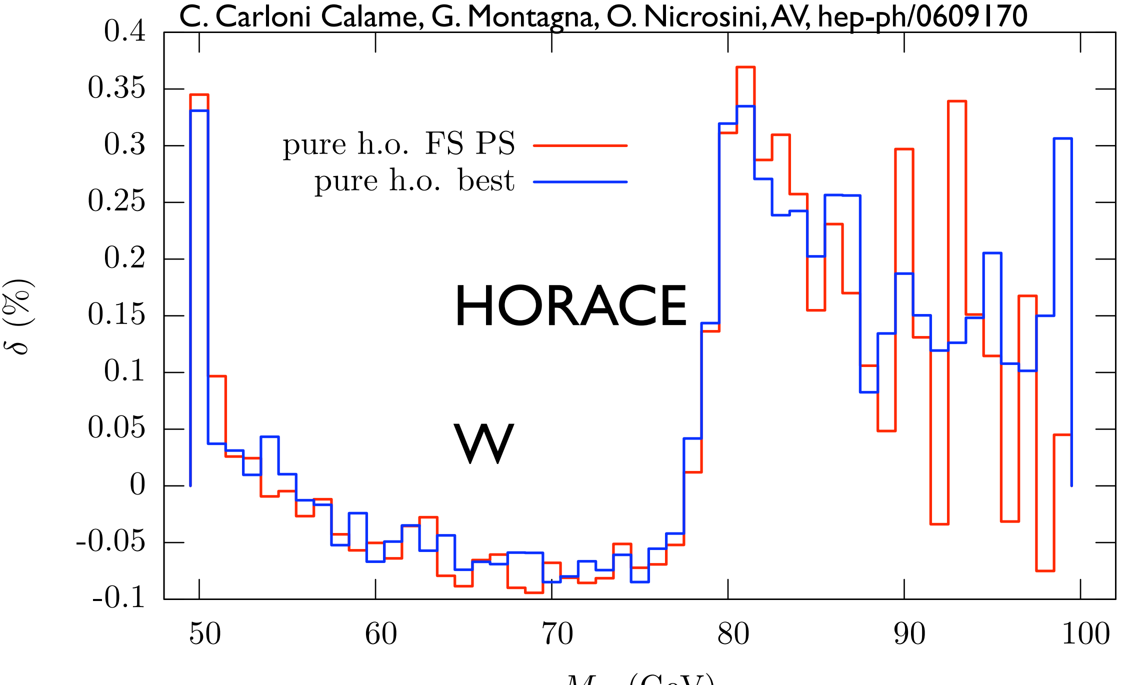


numerical simulation of final state QED multiple photon emission via Parton Shower (Photos, HORACE)

matching of NLO-EW results with complete QED Parton Shower (HORACE)

C. Carloni Calame, G. Montagna, O. Nicrosini, AV, hep-ph/0609170



Shift induced in the extraction of MW from higher order QED effects

$$\Delta M_W^{\alpha} = 110 \text{ MeV}$$

$$\Delta M_W^{exp} = -10 \text{ MeV}$$

Previous combinations of QCD and EW corrections to Drell-Yan

LL approximation in Shower MC

no tuned comparisons on these tools

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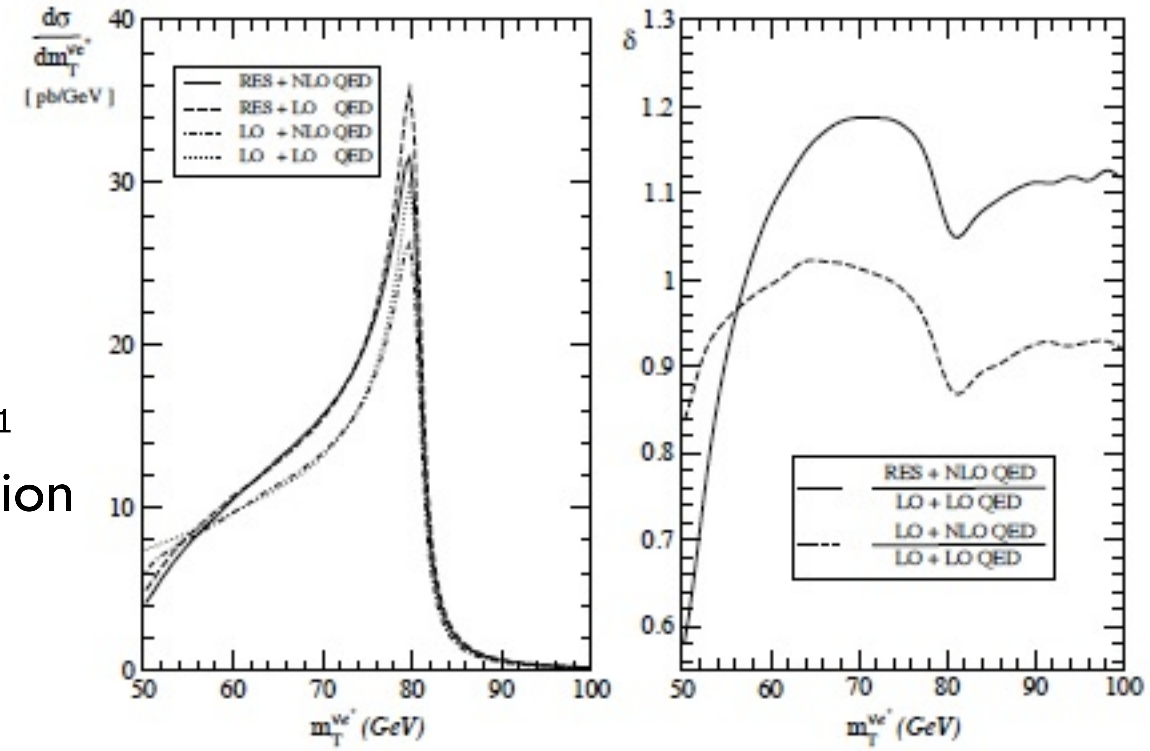

Resbos-A Q.-H. Cao and C.-P. Yuan, Phys. Rev. Lett. **93** (2004) 042001

soft gluon resummation + NLO final state QED radiation

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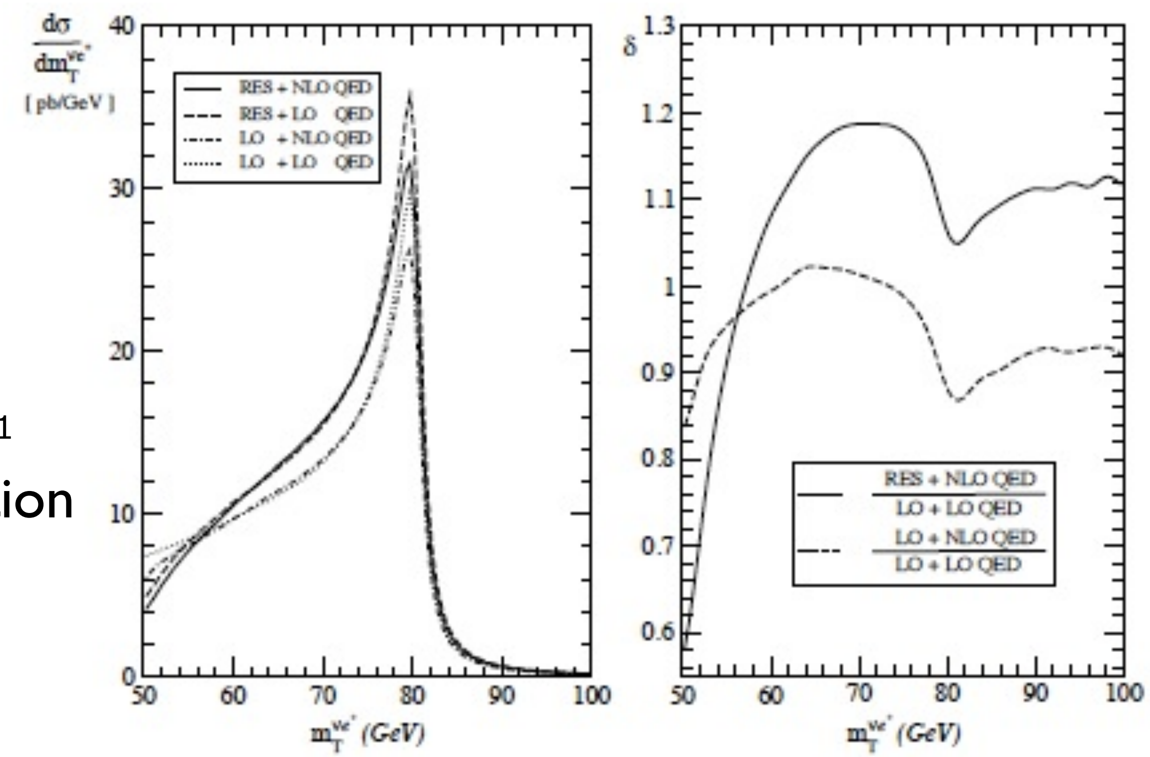

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soft gluon resummation + NLO final state QED radiation

combined use of MC@NLO + HORACE + HERWIG

G. Balossini, C.M.Carloni Calame, G.Montagna, M.Moretti, O.Nicrosini, F.Piccinini, M.Treccani, A.Vicini, JHEP 1001:013, 2010

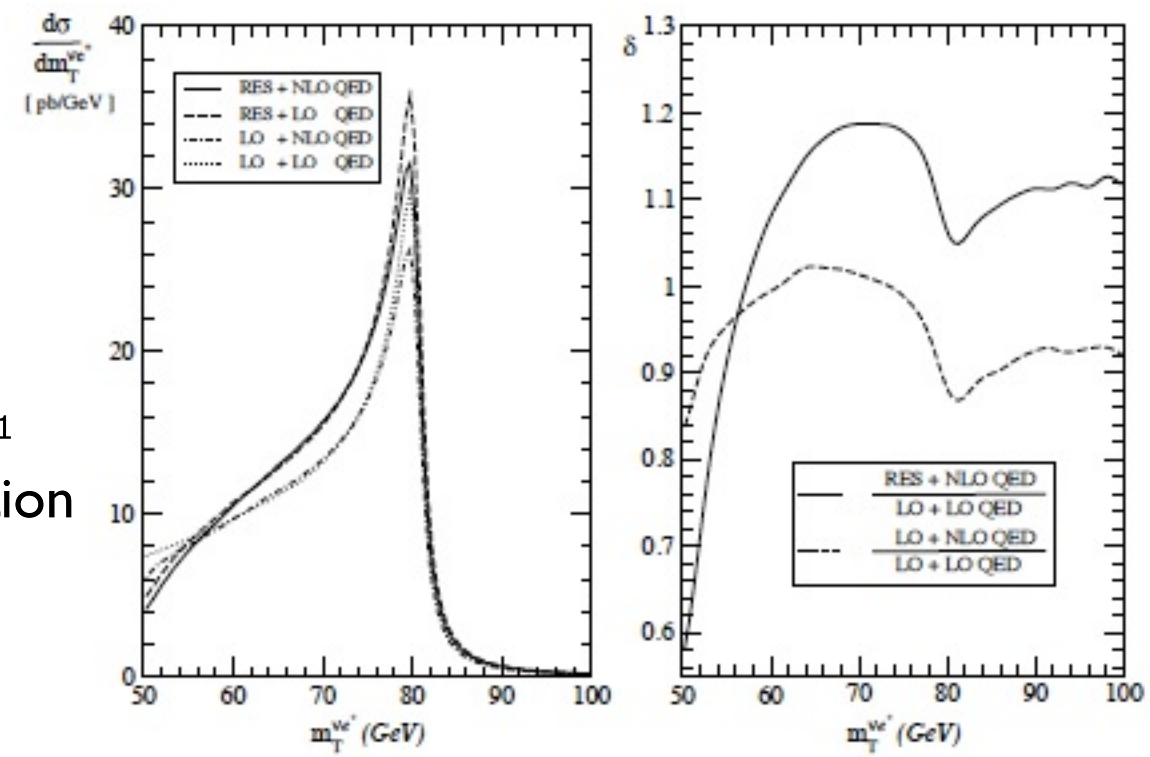
factorized prescription

$$\left[\frac{d\sigma}{d\mathcal{O}}\right]_{QCD\otimes EW} = \left(1 + \frac{\left[\frac{d\sigma}{d\mathcal{O}}\right]_{MC@NLO} - \left[\frac{d\sigma}{d\mathcal{O}}\right]_{HERWIG\ PS}}{\left[\frac{d\sigma}{d\mathcal{O}}\right]_{LO/NLO}}\right) \times \left\{\left[\frac{d\sigma}{d\mathcal{O}}\right]_{EW}\right\}_{HERWIG\ PS}$$

additive prescription

$$\left[\frac{d\sigma}{d\mathcal{O}}\right]_{QCD\oplus EW} = \left\{\frac{d\sigma}{d\mathcal{O}}\right\}_{QCD} + \left\{\left[\frac{d\sigma}{d\mathcal{O}}\right]_{EW} - \left[\frac{d\sigma}{d\mathcal{O}}\right]_{Born}\right\}_{HERWIG\ PS}$$

Previous combinations of QCD and EW corrections to Drell-Yan



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see also:

the combination of MC@NLO+PHOTOS in N.Adam, V.Halyo, S.Yost, W.Zhu, JHEP 0809:133,2008

the (QCD+EW) combination in S.Jadach, M.Skrzypek, P.Stephens, Z.Was, W.Placzek, Acta.Phys.Polon.B38:2305 (2007)

Recent developments of QCD and EW corrections to Drell-Yan

FEWZ, NC-DY : NNLO-QCD + NLO-EW additive combination

Li, Petriello, arXiv:1208.5967

POWHEG, CC-DY: NLO-(QCD+EW) matched with QCD/QED Parton Shower

Bernaciak, Wackeroth, arXiv:1201.4804

Barzè, Montagna, Nason, Nicrosini, Piccinini, arXiv:1202.0465

POWHEG, NC-DY: NLO-(QCD+EW) matched with QCD/QED Parton Shower

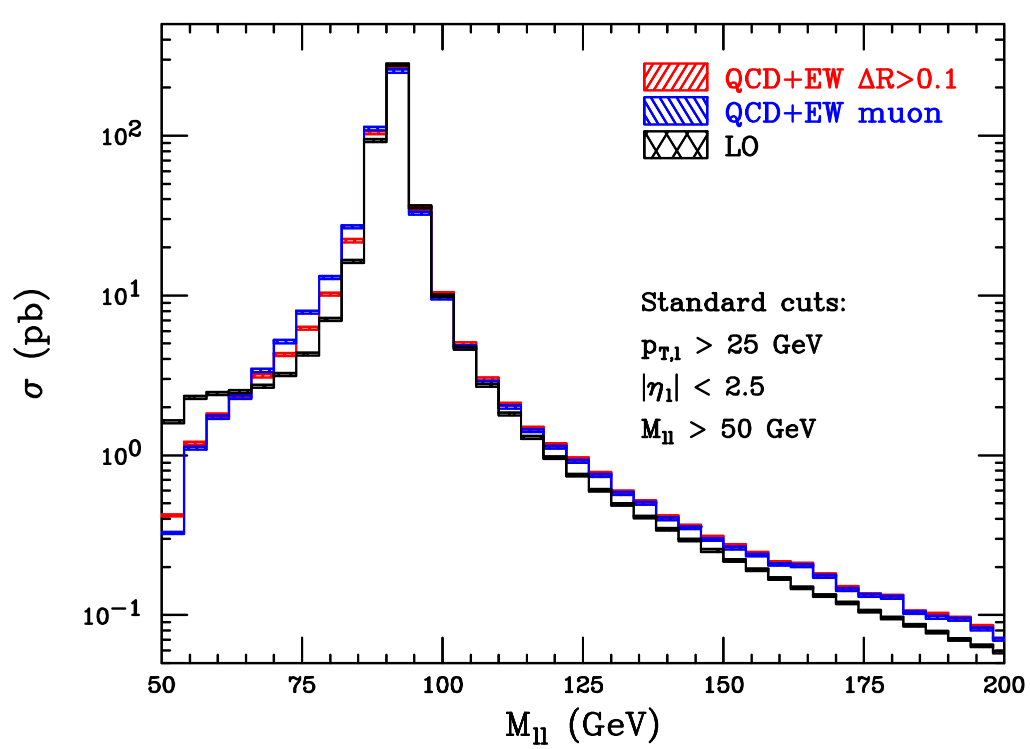
Barzè, Montagna, Nason, Nicrosini, Piccinini, Vicini, arXiv:1302.4606

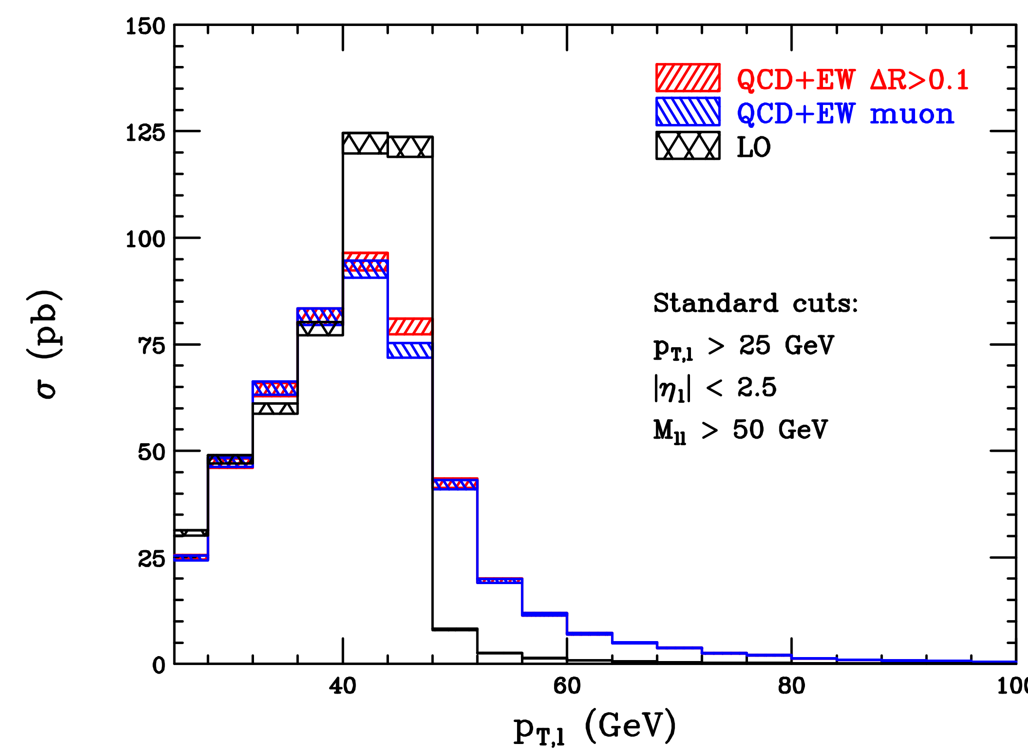
Inclusion in FEWZ of exact O(α) EW corrections to NC-DY

FEWZ,   NC-DY   :   NNLO-QCD + NLO-EW   additive combination

Li, Petriello, arXiv:1208.5967

$$\mathcal{O} = \mathcal{O}_{LO}\left(1+\delta_{QCD}^{NLO+NNLO}+\delta_{EW}^{NLO}\right)$$





- accurate prediction of the invariant mass distribution
- missing effects of multiple photon radiation (few % in the tails)

- the large bins avoid the appearance of the double peak structure typical of fixed order results

Inclusion in POWHEG of the exact O(α) EW corrections

POWHEG, CC-DY: NLO-(QCD+EW) matched with QCD/QED Parton Shower

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http://powhegbox.mib.infn.it/

$$d\sigma = \sum_{f_b} \bar{B}^{f_b}(\Phi_n) d\Phi_n \left\{ \Delta^{f_b}\left(\Phi_n, p_T^{min}\right) + \sum_{\alpha_r \in \{\alpha_r | f_b\}} \frac{\left[d\Phi_{rad}\, \theta(k_T - p_T^{min})\, \Delta^{f_b}(\Phi_n, k_T)\, R(\Phi_{n+1}) \right]_{\alpha_r}^{\bar{\Phi}_n^{\alpha_r} = \Phi_n}}{B^{f_b}(\Phi_n)} \right\}$$

(differential)
overall normalization factor
exact NLO QCD+EW accuracy
(Born+virtual+integrated real)

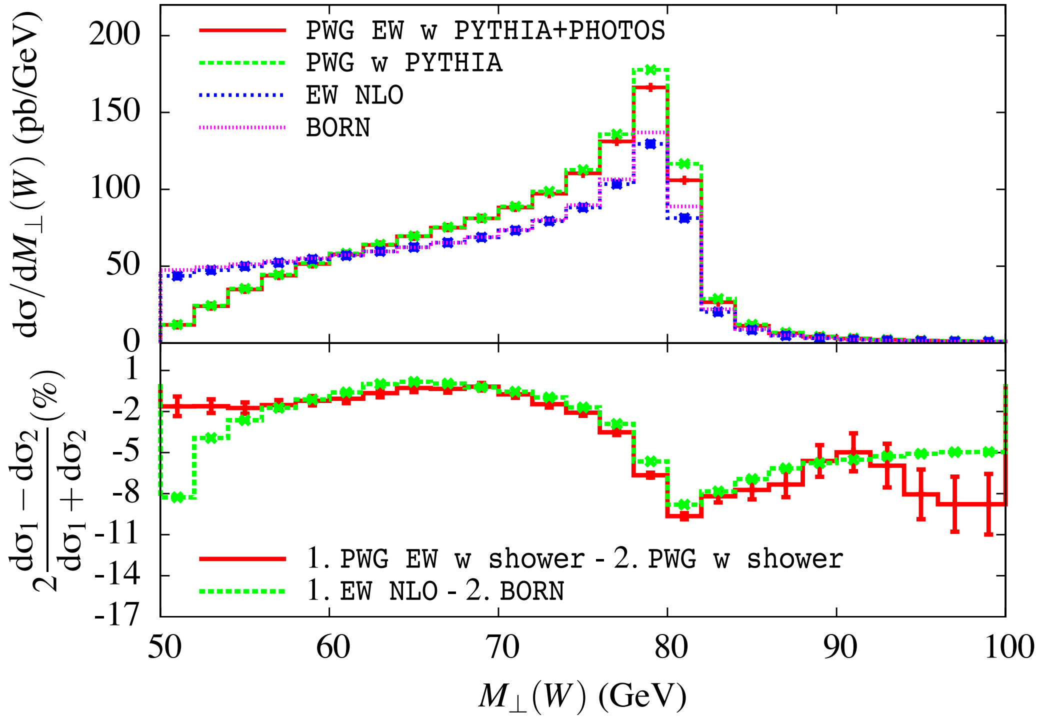
no emission probability
(Sudakov form factor)

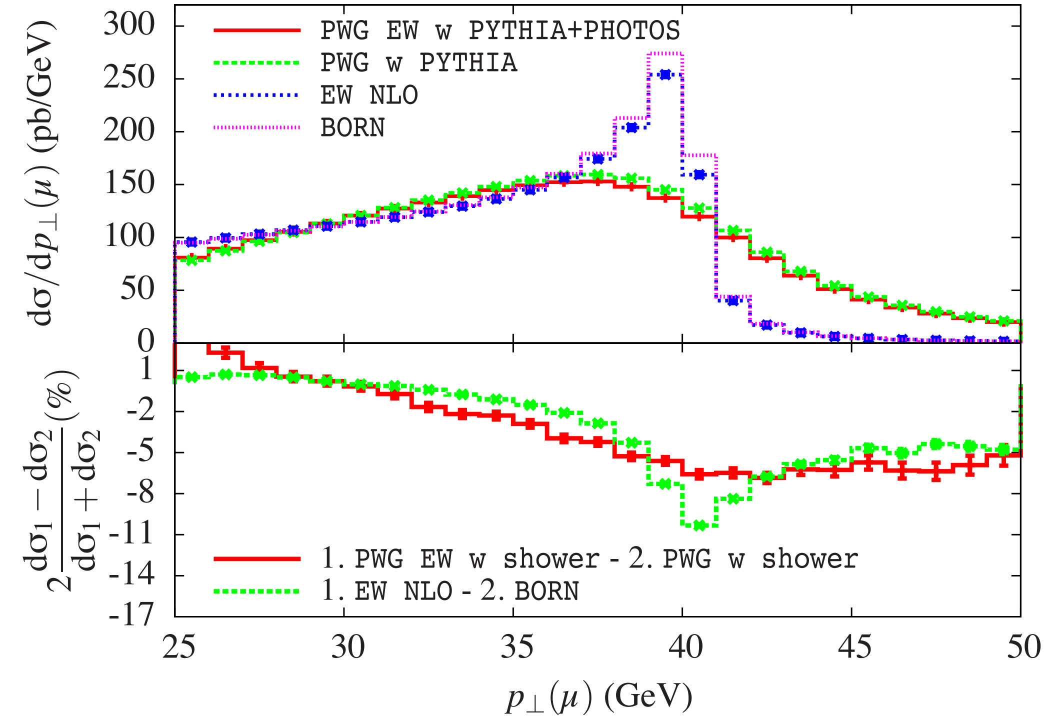
emission probability of one parton
requested to be the hardest emission
(Sudakov form factor)

- the events generated in this way are then passed to PYTHIA/HERWIG for showering
- the effect of radiative corrections on the distributions is ruled by the (modified) Sudakov form factor and is factorized w.r.t. the lowest order kinematics B

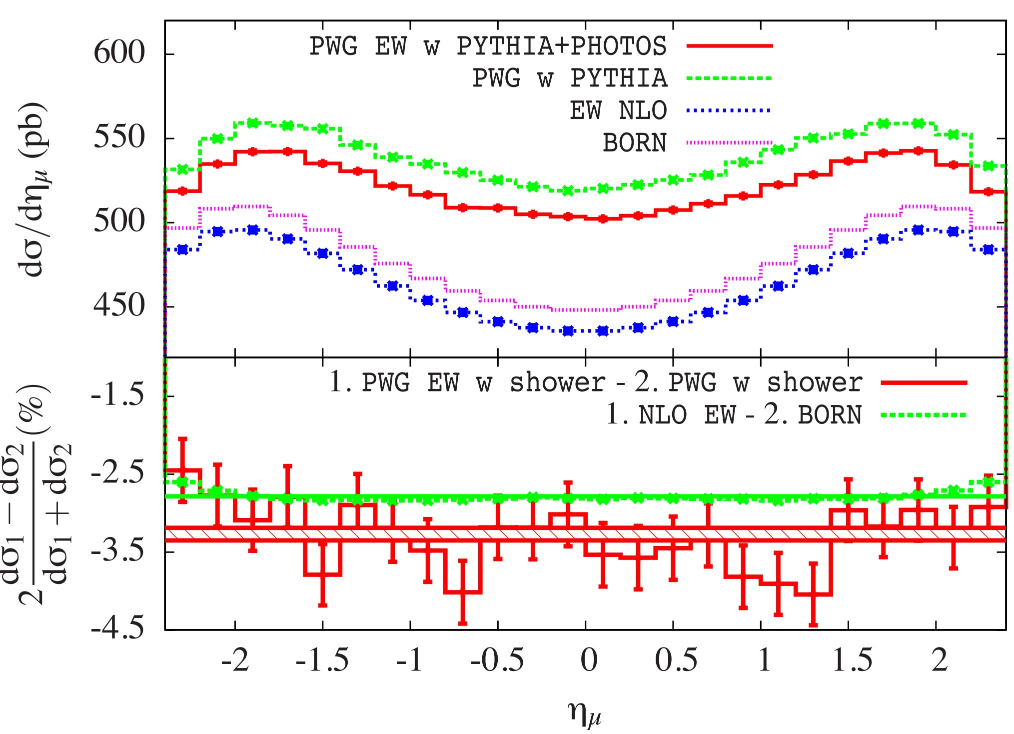
CC-DY: BMNNP results

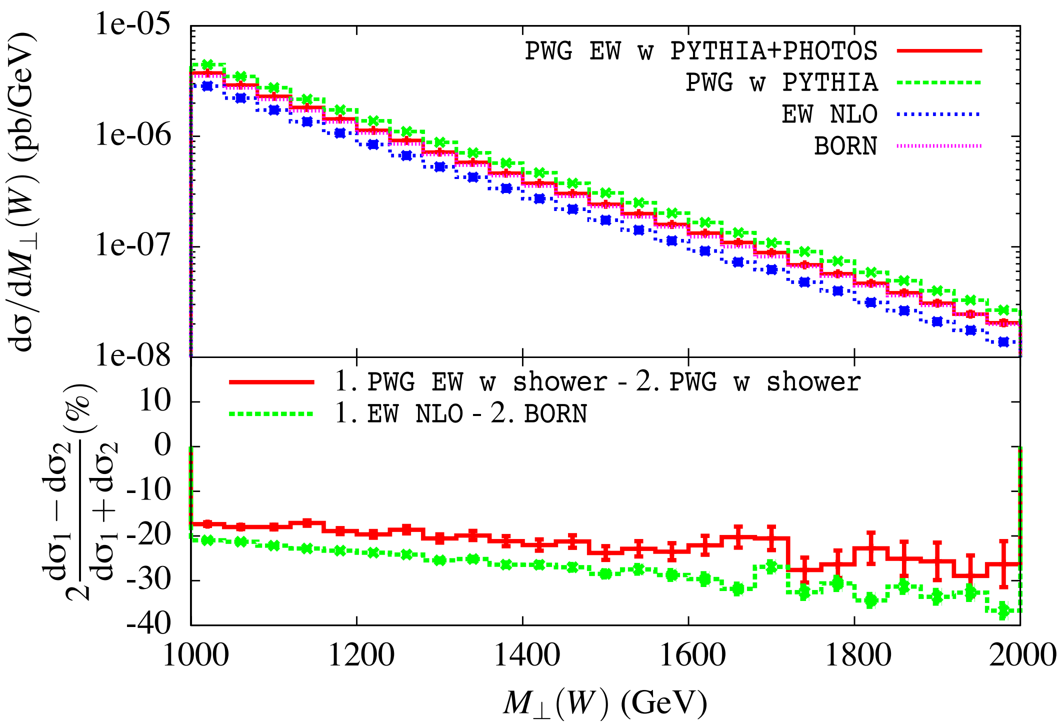
Barzè, Montagna, Nason, Nicrosini, Piccinini, arXiv:1202.0465





- all the results in the Gμ input scheme; multiple photon radiation included with PHOTOS
- the transverse mass is stable against QCD corrections → also the NLO-EW effects are preserved after showering
- the lepton transverse momentum is more sensitive to multiple gluon radiation
  the sharp peak due to EW corrections is reduced by the QCD-Parton Shower
- the interplay between QCD and EW corrections yields effects at the per cent level





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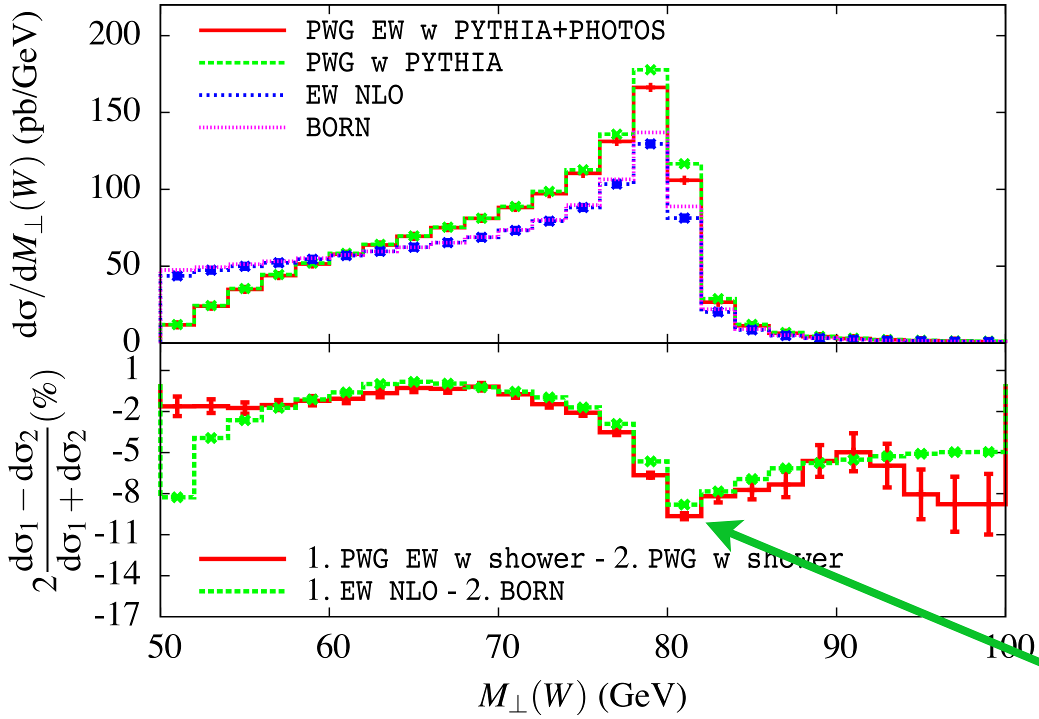

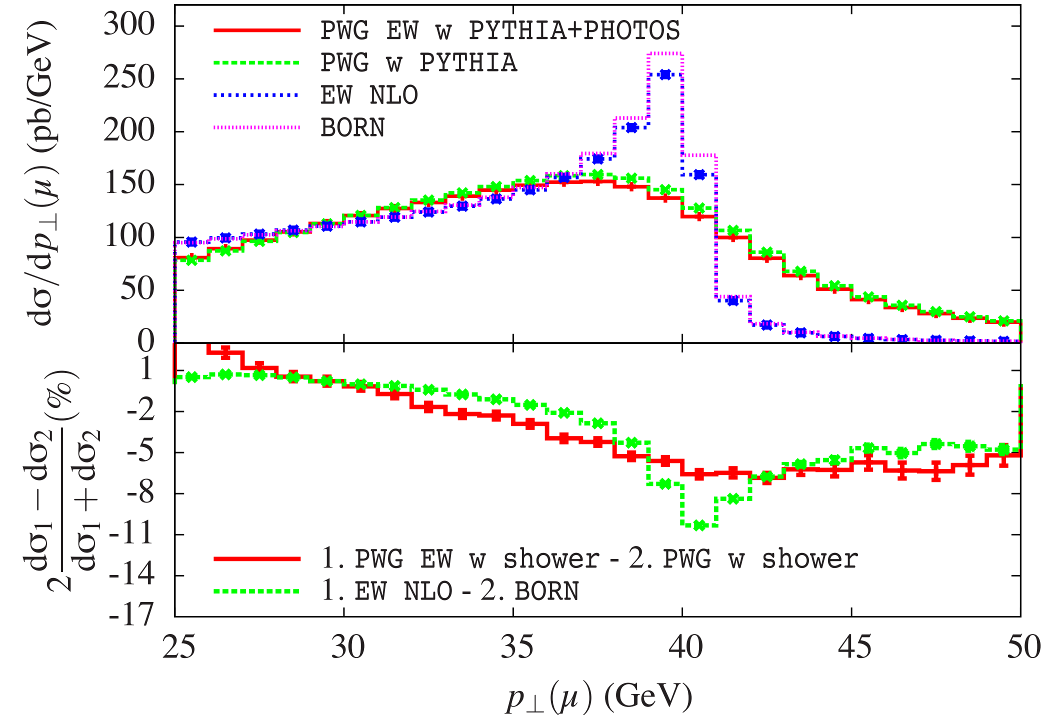

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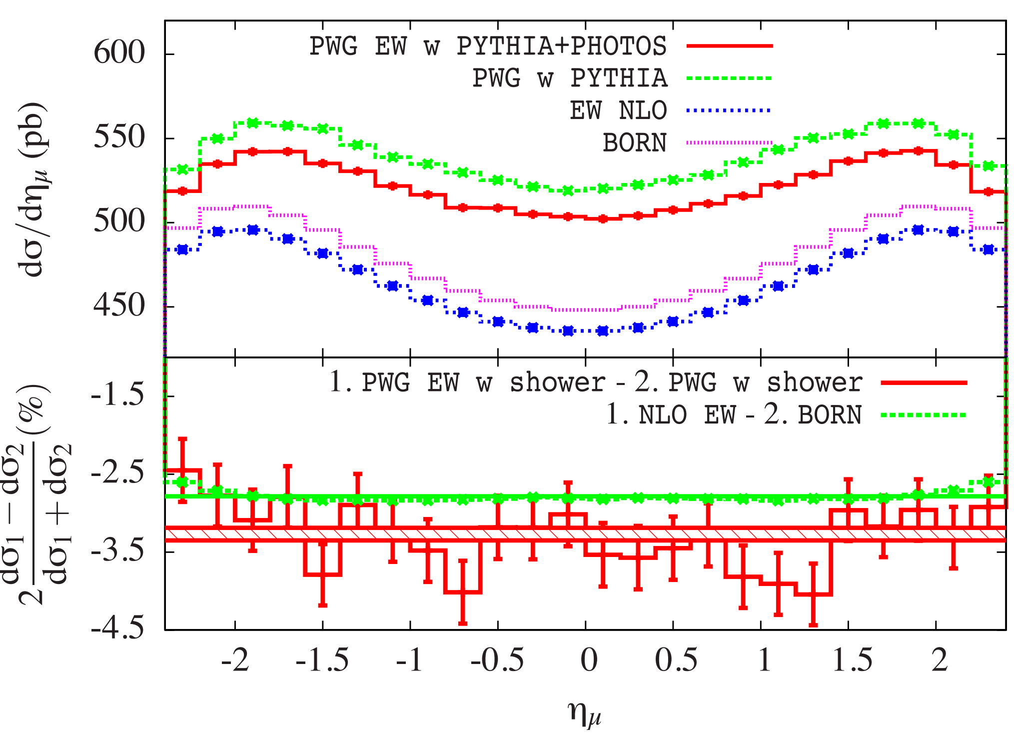

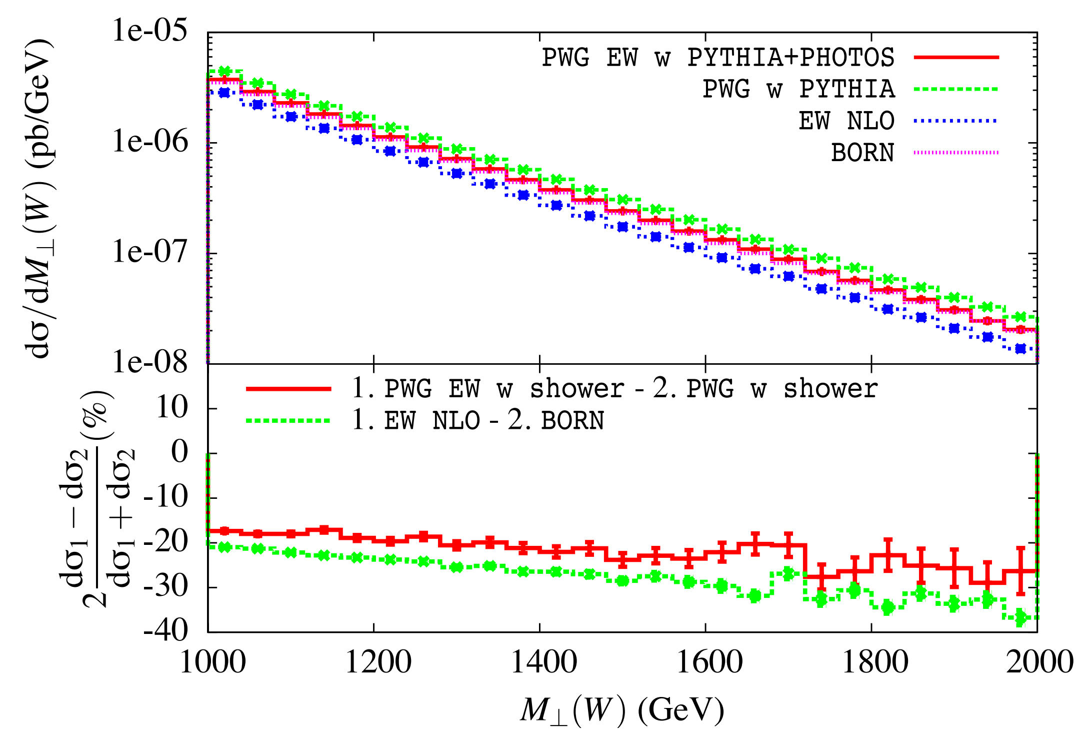

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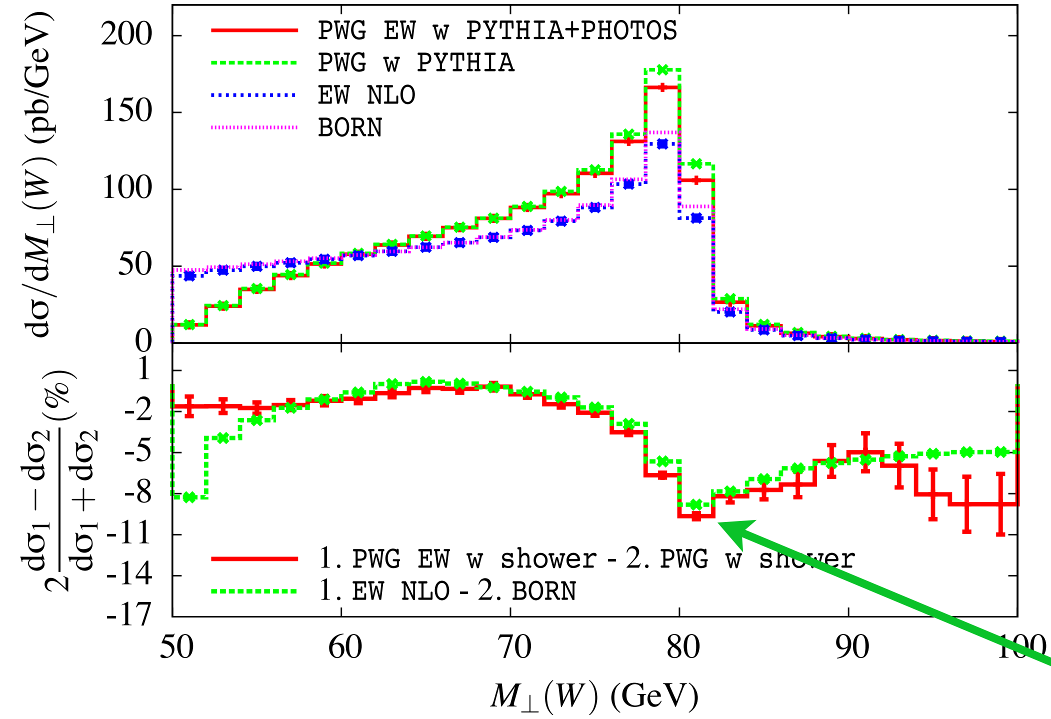
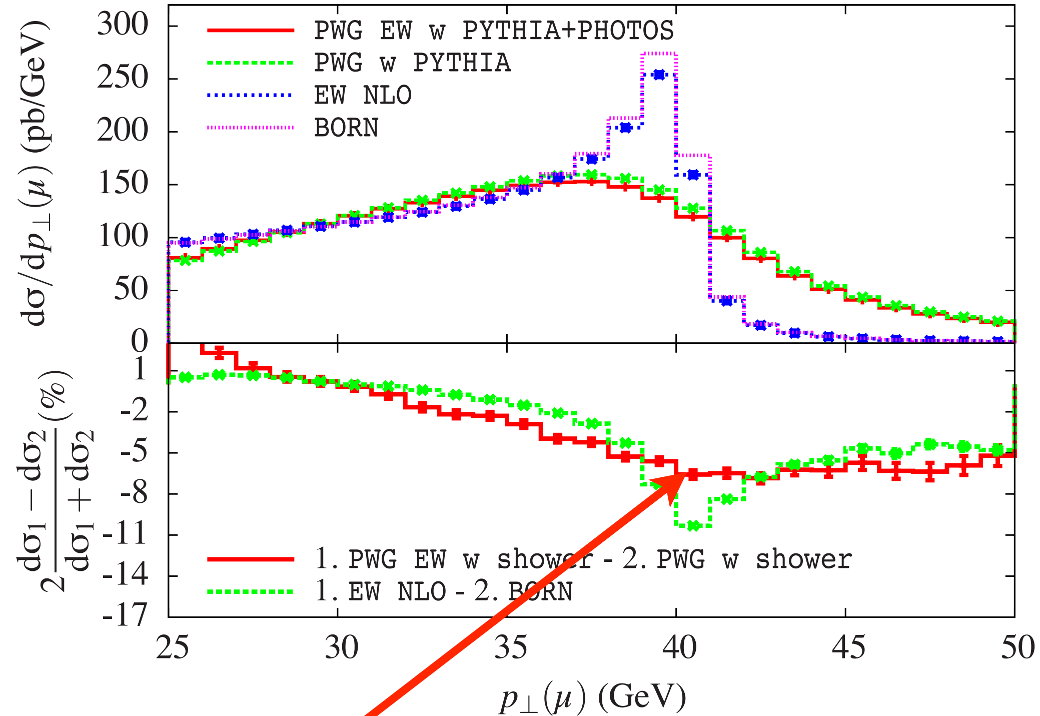
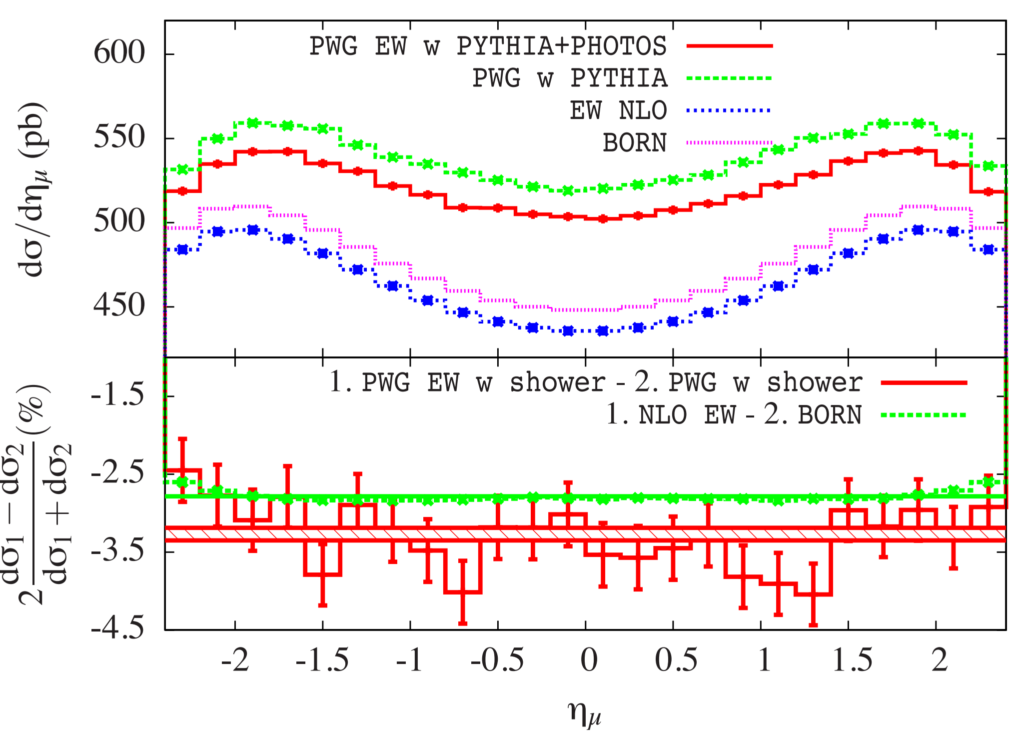
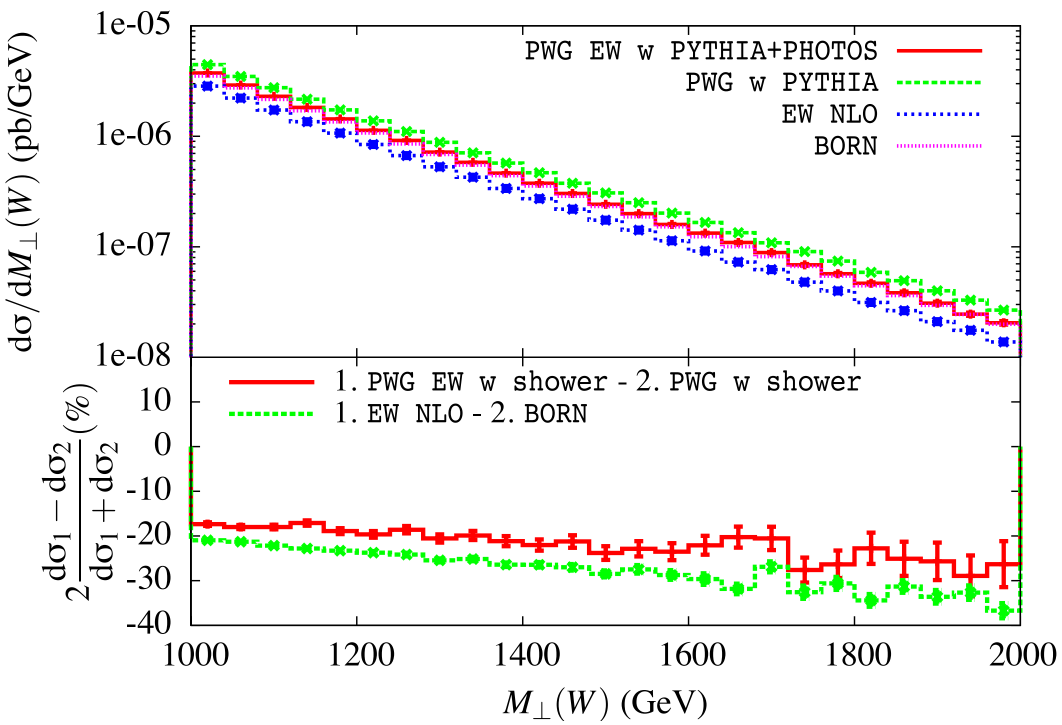




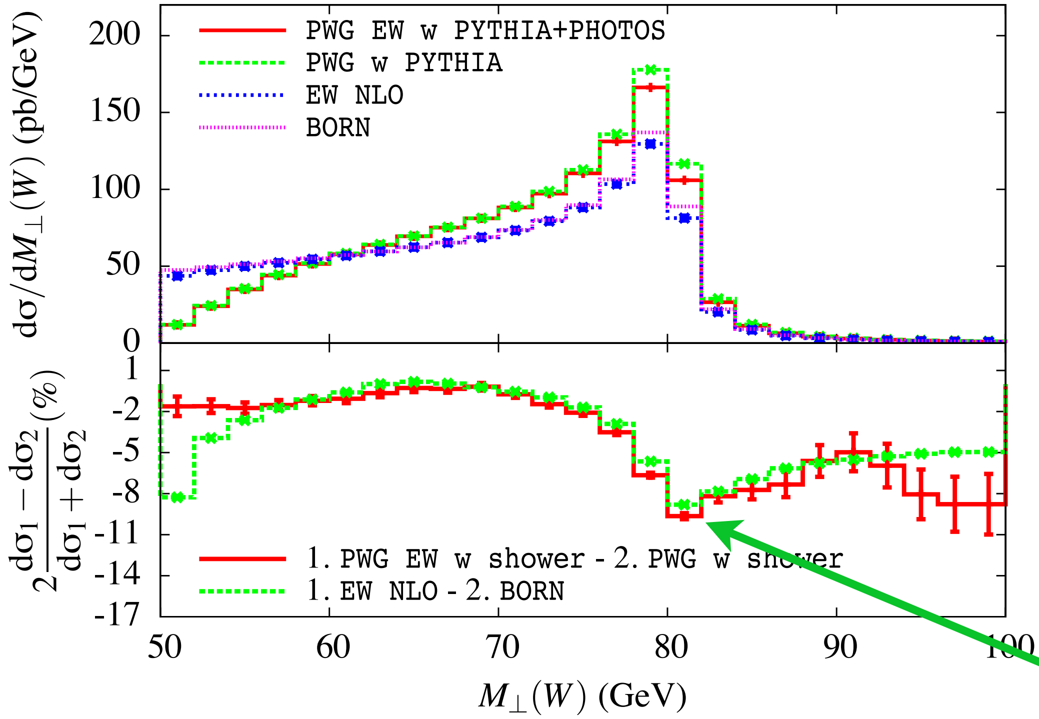
- all the results in the Gμ input scheme; multiple photon radiation included with PHOTOS
- the transverse mass is stable against QCD corrections → also the NLO-EW effects are preserved after showering
- the lepton transverse momentum is more sensitive to multiple gluon radiation
  the sharp peak due to EW corrections is reduced by the QCD-Parton Shower
- the interplay between QCD and EW corrections yields effects at the per cent level

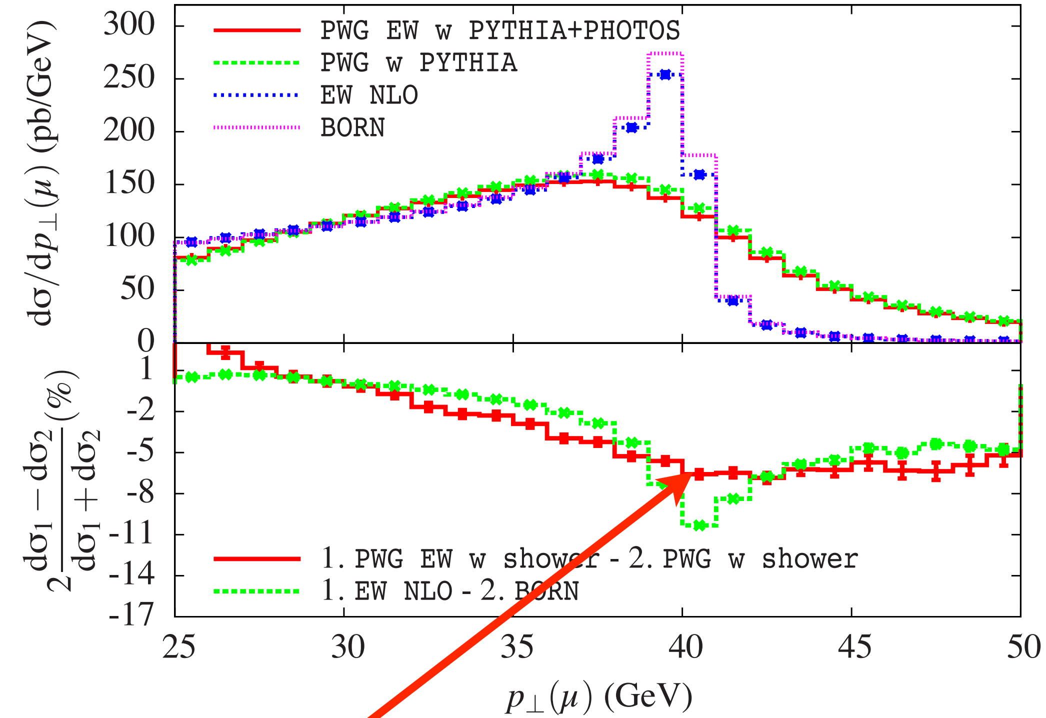




CC-DY: BMNNP results

Barzè, Montagna, Nason, Nicrosini, Piccinini, arXiv:1202.0465





- all the results in the Gμ input scheme; multiple photon radiation included with PHOTOS
- the transverse mass is stable against QCD corrections → also the NLO-EW effects are preserved after showering
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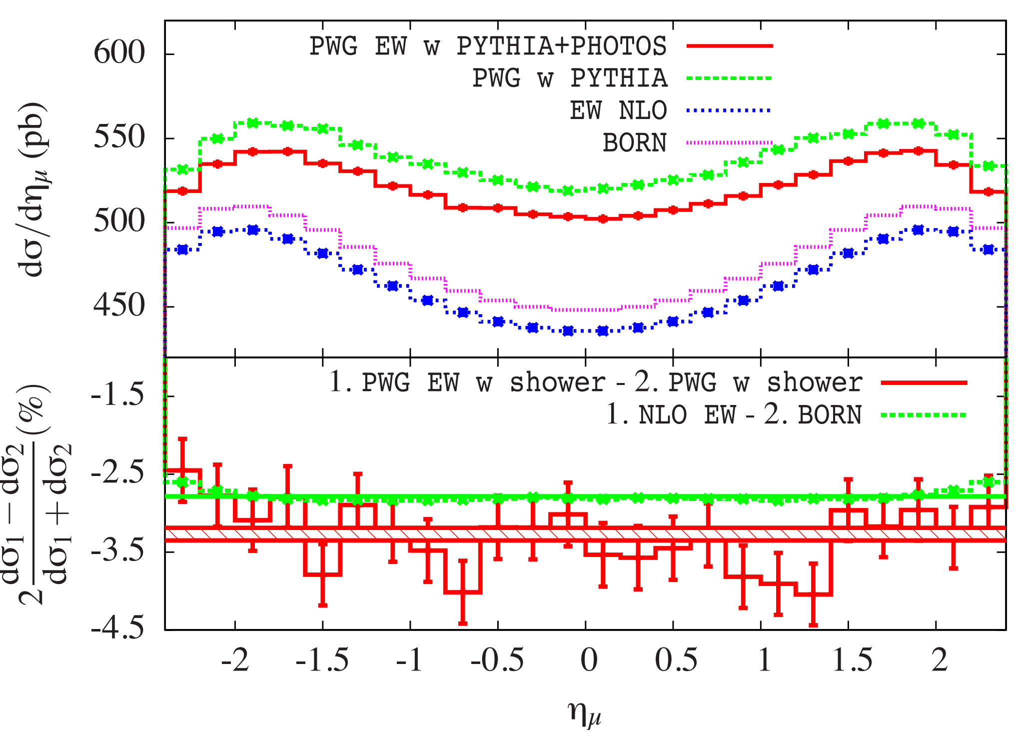
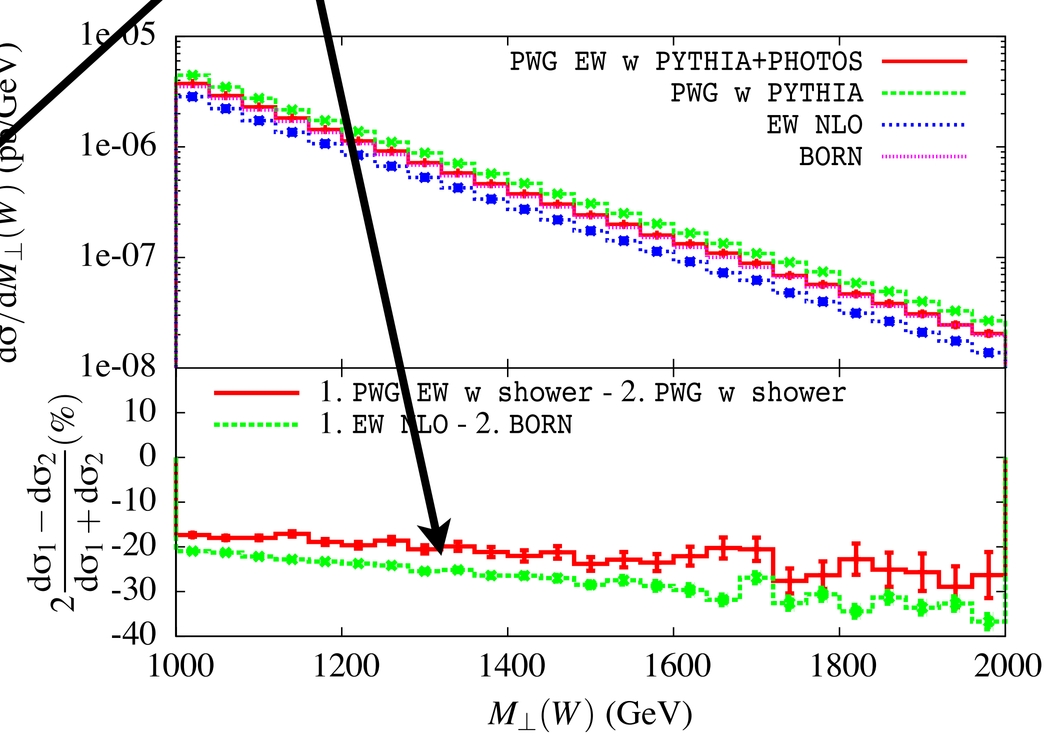
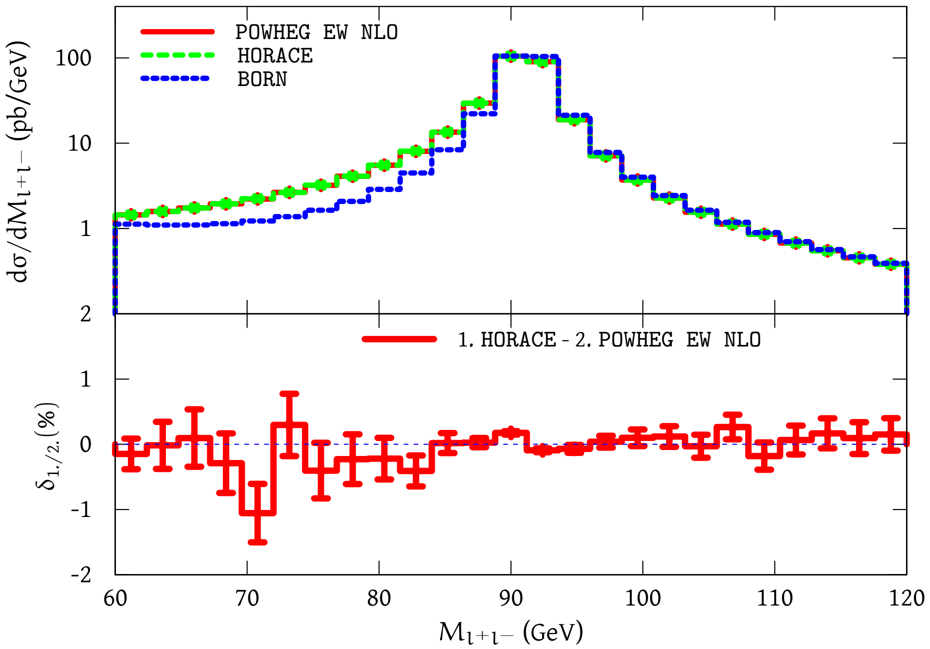
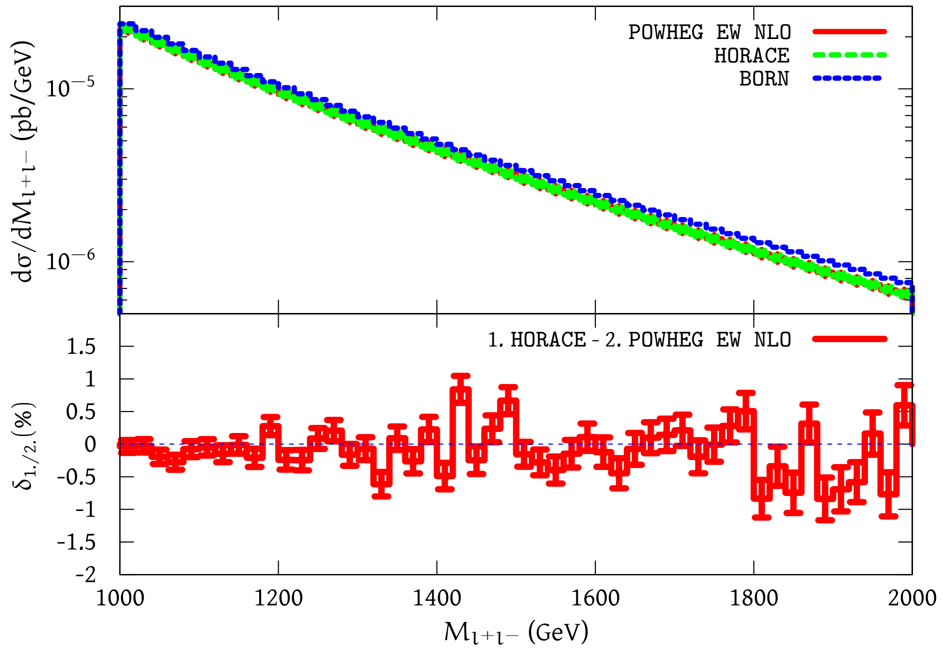


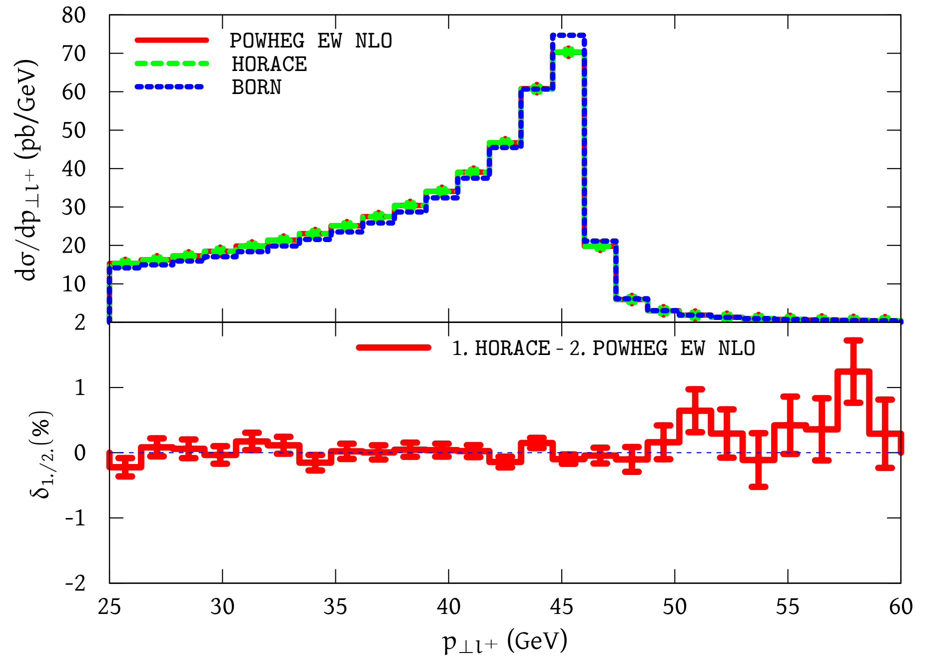


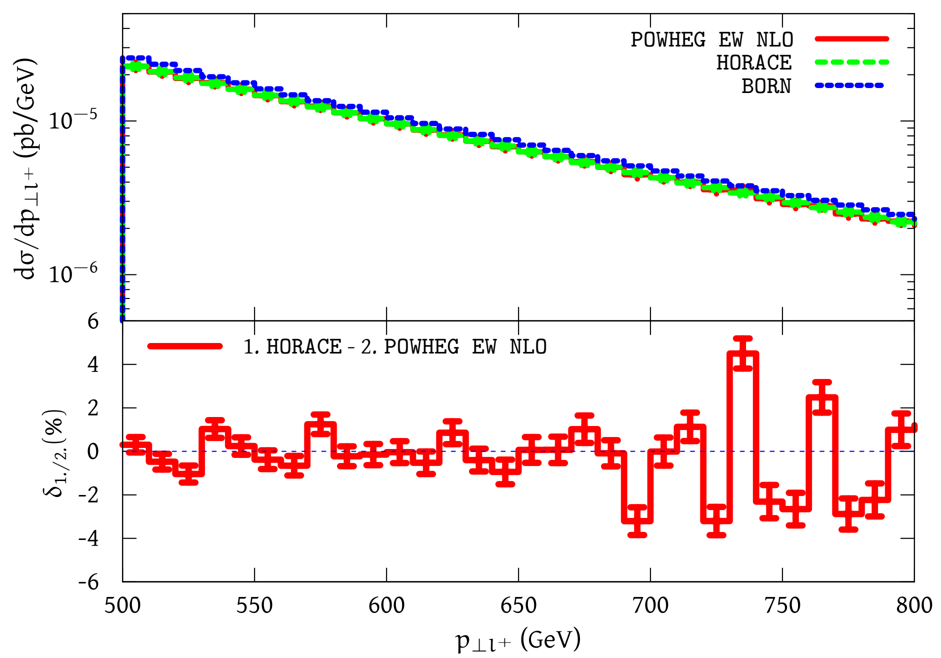
NC-DY: QCD+EW effects check of NLO-EW against HORACE

Barzè, Montagna, Nason, Nicrosini, Piccinini, Vicini, arXiv:1302.4606





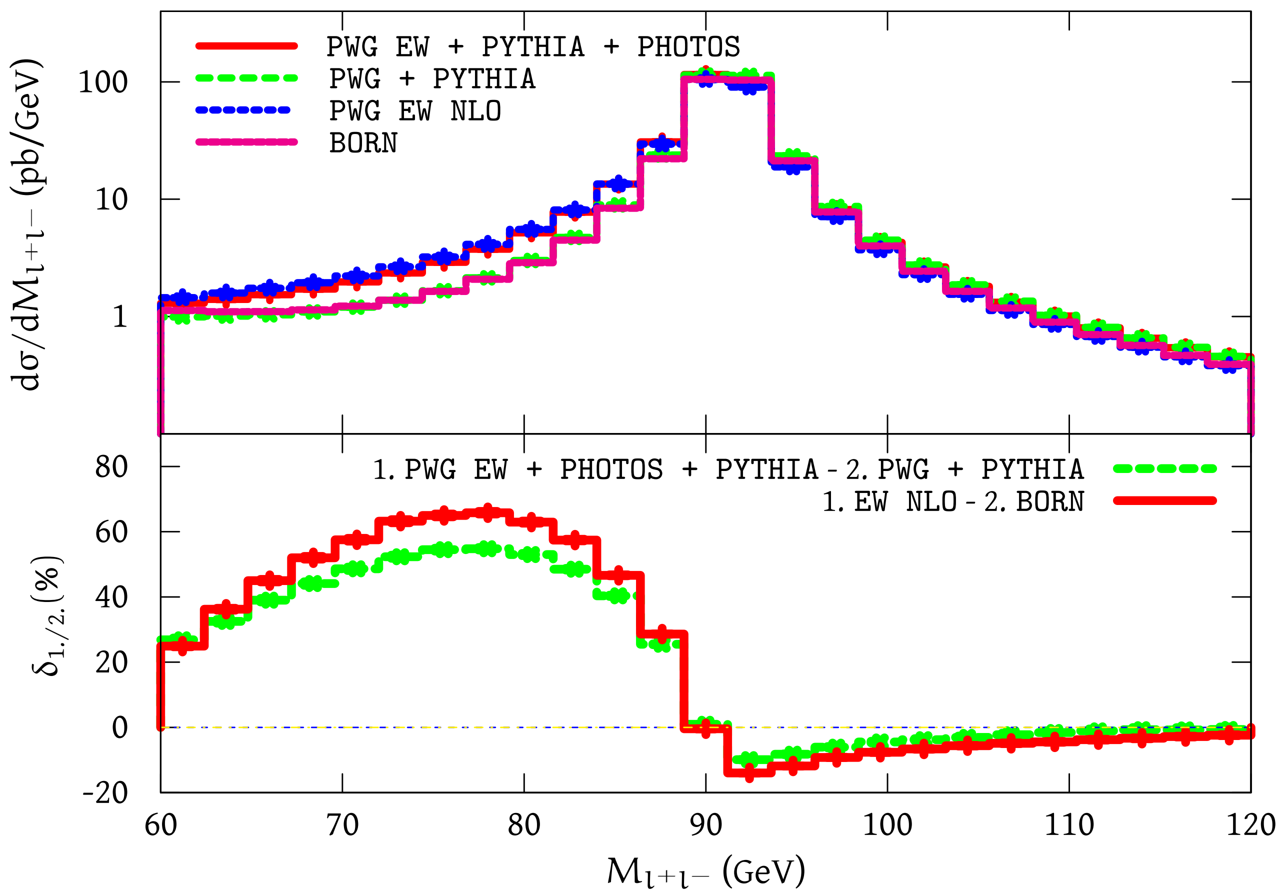


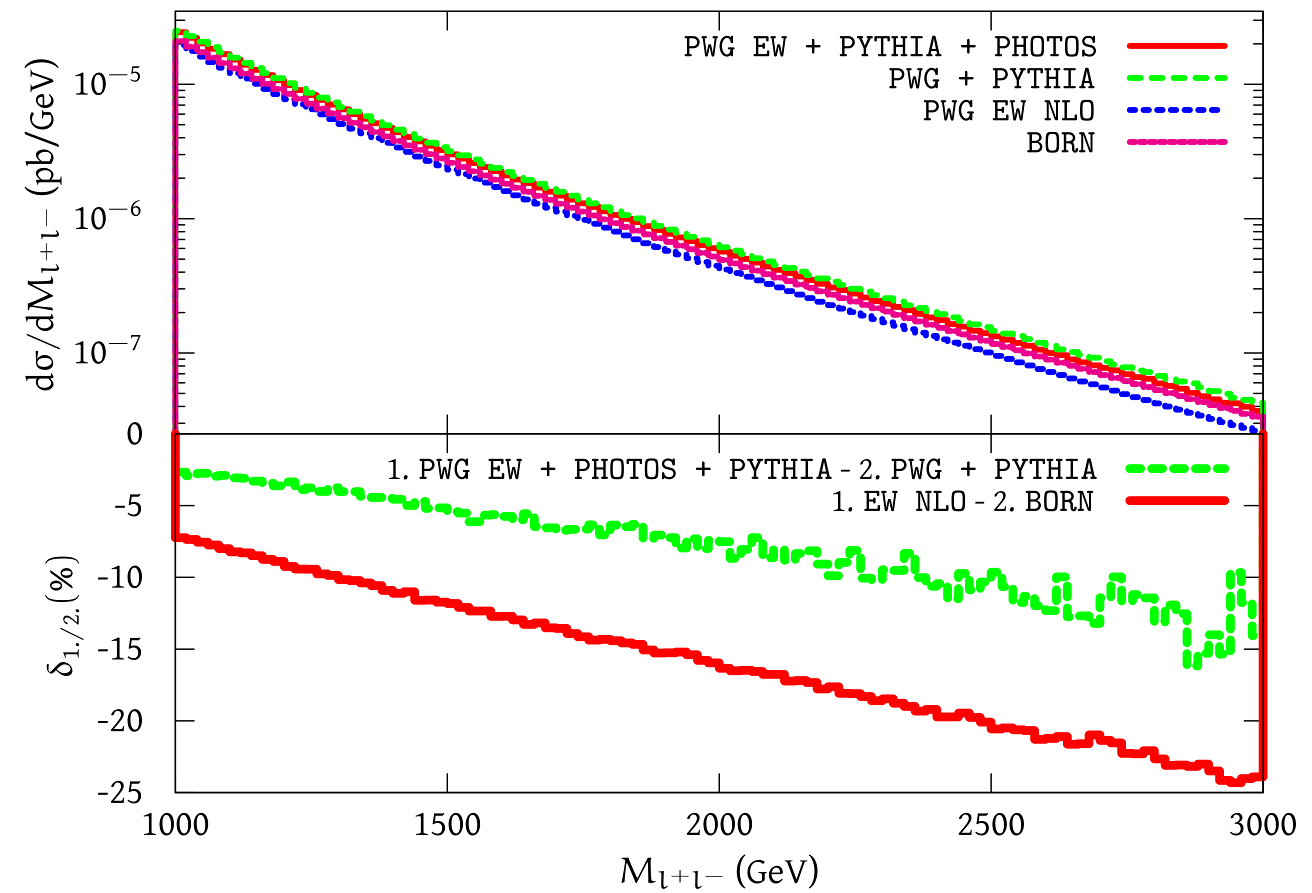


- the NLO-EW corrections in POWHEG have been computed independently of previous calculations and cross-checked against the results by HORACE

NC-DY: QCD+EW effects   lepton-pair invariant mass distribution

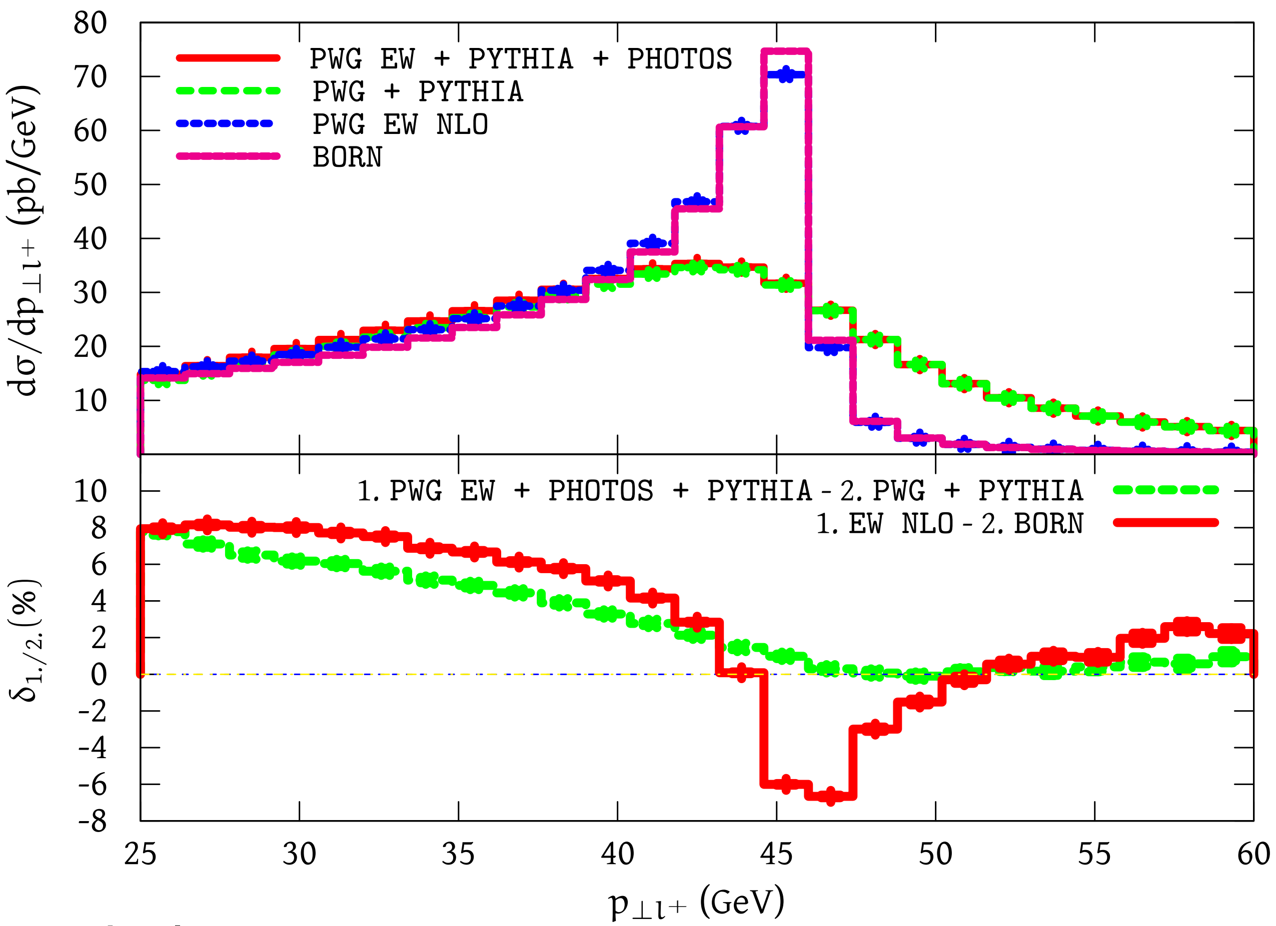
Barzè, Montagna, Nason, Nicrosini, Piccinini, Vicini, arXiv:1302.4606





- all the results in the α_0 input scheme; first photon emission is described exactly with matrix elements
  FSR multiple photon radiation included with PHOTOS, ISR with PYTHIA
- the invariant mass is stable against QCD corrections → the bulk of the NLO-EW effects are preserved after showering
- the interplay between QCD and EW corrections of O(αα_s) yields effects at the per cent level in the peak region
  at the 10% level in the tails

NC-DY: QCD+EW effects lepton transverse momentum

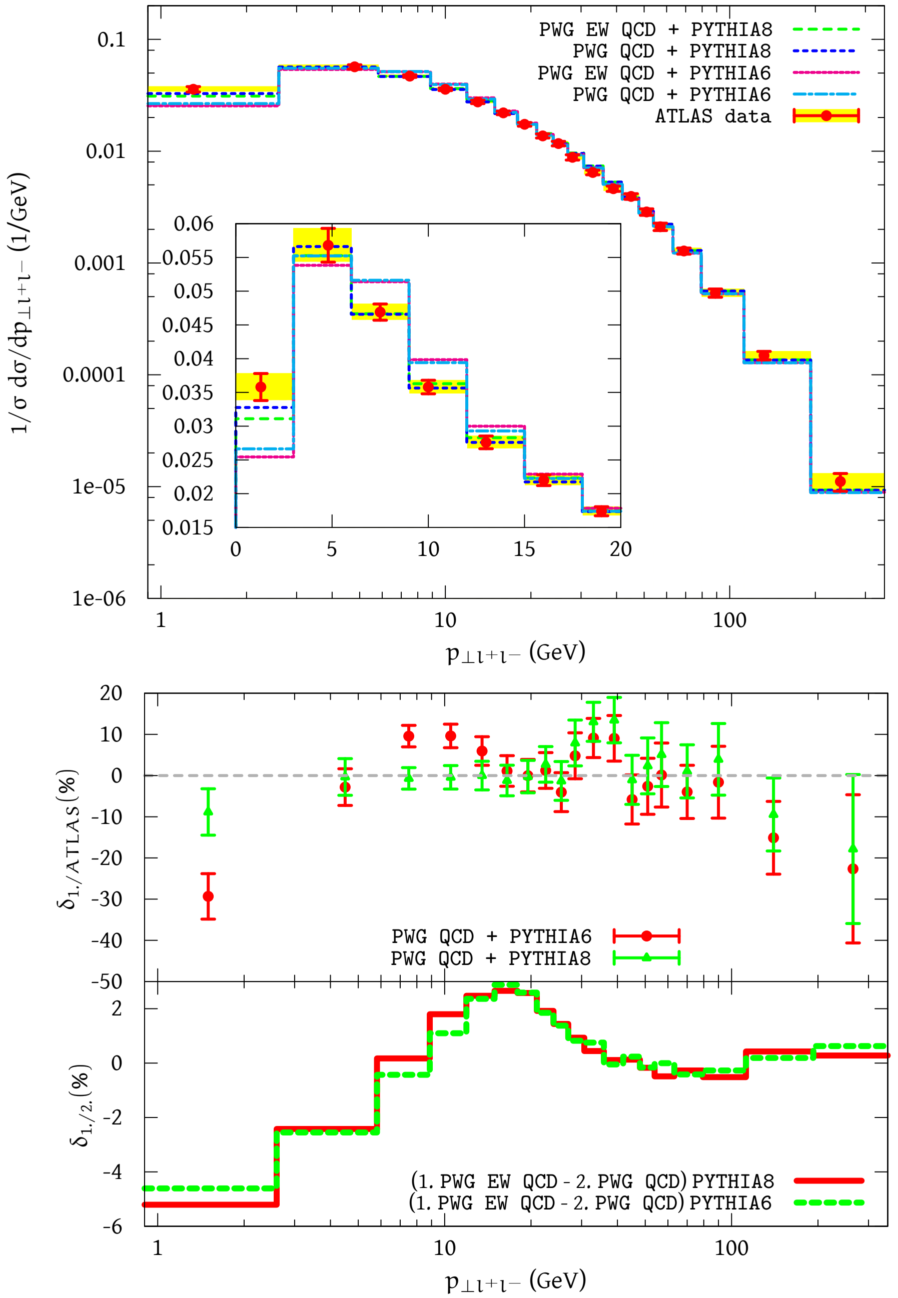


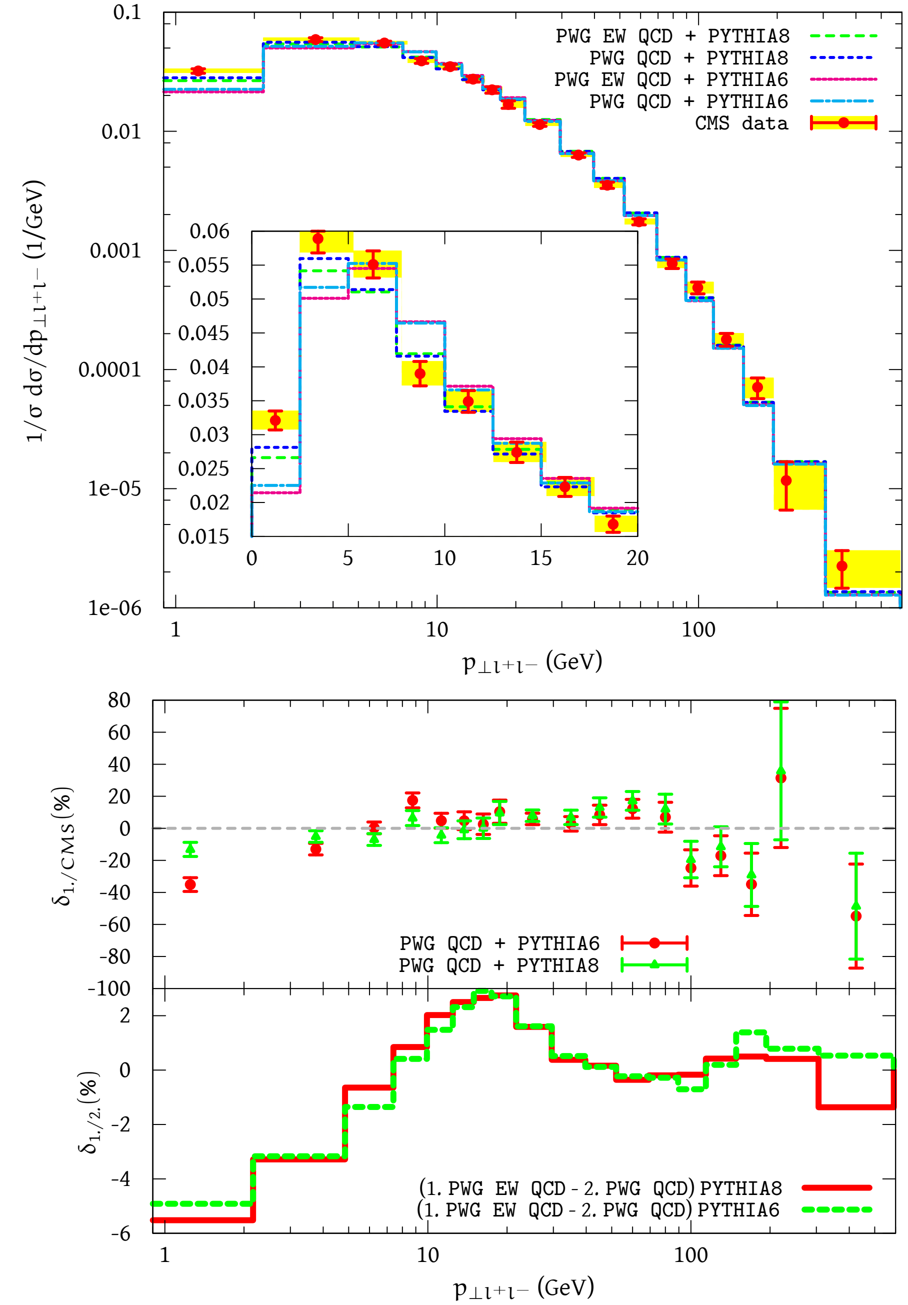
- the lepton transverse momentum is very sensitive to multiple gluon radiation
- the sharp peak due to EW corrections is reduced by the interplay with the QCD-Parton Shower;
  factorizable $O(\alpha\alpha_s)$ corrections are at the level of 7%
- an additive prescription to combine QCD+EW effects instead preserves the peak

the fixed-order QCD description of the lepton transverse momentum distribution is poor, a resummation is needed

the combination of NLO-EW effects with multiple gluon emission strongly smears both
the NLO-QCD fixed order spectrum and the peaked NLO-EW correction

NC-DY: QCD+EW effects lepton-pair transverse momentum





- the description of the lepton-pair transverse momentum distribution data is in general good
- default values for the non-perturbative parameters in PYTHIA6 and PYTHIA8 have been used (further tuning possible)
- full NLO-EW matrix element → bulk of the QED effects on ptZ; multiple photon radiation has negligible impact
- QED radiation affects differently ptW and ptZ, both in its FSR and in its ISR components
  POWHEG (QCD+EW) for CC- and NC-DY allows to disentangle the different QED effects
  from the common pattern of the QCD corrections

Inclusion in POWHEG of the exact O(α) corrections (NLO-EW)

$$d\sigma = \sum_{f_b} \bar{B}^{f_b}(\Phi_n) d\Phi_n \left\{ \Delta^{f_b}\left(\Phi_n, p_T^{min}\right) + \sum_{\alpha_r \in \{\alpha_r | f_b\}} \frac{\left[d\Phi_{rad}\ \theta(k_T - p_T^{min})\ \Delta^{f_b}(\Phi_n, k_T)\ R(\Phi_{n+1})\right]_{\alpha_r}^{\bar{\Phi}_n^{\alpha_r} = \Phi_n}}{B^{f_b}(\Phi_n)} \right\}$$

- the POWHEG basic formula · is additive in the overall normalization,
  · it describes exactly one parton emission (photon/gluon/quark) (but NOT two partons)
  · includes in a factorized form mixed and higher order corrections relevant in the distributions
  in particular the bulk of the O(αα_s) corrections
  (but it has NOT O(αα_s) accuracy)

- difference with respect to

$$\mathcal{O} = \mathcal{O}_{LO}\left(1 + \delta_{QCD}^{NLO+NNLO} + \delta_{EW}^{NLO}\right)$$

1) purely additive prescription

$$\mathcal{O} = \mathcal{O}_{LO}\left(1 + \delta_{QCD}^{NLO+NNLO}\right)\left(1 + \delta_{EW}^{NLO}\right)$$

2) factorized use of (differential) K-factors

· POWHEG accounts for multiple emission effects
· the kinematics of multiple emissions is exact (fully differential)

- the subtraction of IS QED collinear singularities is consistent only with MRST2004QED, where the evolution kernel of the parton densities includes also a QED term; updated PDF set including QED effects will be welcome!

Uncertainties on MW from Tevatron measurement. arXiv:1204.0042

Source	Uncertainty (MeV)
Lepton energy scale and resolution	7
Hadronic recoil energy scale and resolution	6
Lepton removal	2
Backgrounds	3
Experimental subtotal	10
Parton distributions	10
QED radiation	4
$p_T(W)$ model	5
Production subtotal	12
Total systematic uncertainty	15
W-boson statistics	12
Total uncertainty	19

Table 1: Uncertainties for the combined result on M_W from CDF [?].

- the estimate of the QED error is based on a comparison between PHOTOS, W/ZGRAD2 and HORACE; at this level of accuracy a full EW study is necessary
  the new POWHEG QCD+EW offers the possibility to perform a consistent, exact at NLO, combined analysis

- the pQCD uncertainty is absent and is traded for the uncertainty on P_T(W)
  analytical tools like DYqT can help to quantify the QCD uncertainty, by appropriate choice and variation of renormalization, factorization and resummation scales
  how good is the description of the data in pure pQCD?

- which combination of tools provides the best accuracy on each observable?
  · POWHEG NLO-(QCD+EW)
  · DYqT+PHOTOS, ResBos+PHOTOS
  · FEWZ NNLO-QCD + NLO-EW
  the answer to this question requires a systematic benchmarking of the codes

On-going benchmarking study within the LHC-EWWG

see http://lpcc.web.cern.ch/lpcc/

- the authors of the following codes are actively participating to this study
  - HORACE, RADY, SANC, WZGRAD
  - PHOTOS, WINHAC
  - DYNNLO, FEWZ
  - POWHEG (only QCD and QCD+EW)

- in a first phase, technical agreement (same inputs ⇒ same outputs)

  at LO, NLO-QCD, NLO-EW has been reached on differential distributions at better than 0.5% level

- given this common starting point with NLO accuracy,
  we are now exploring the impact of higher order corrections (pure QCD, pure EW, mixed QCDxEW)
  - corrections available only in some codes (e.g. NNLO-QCD vs QCD-PS)
  - ambiguities which can not be fixed without an explicit full next-order calculation (e.g. EW inputs)

ResBos update

M. Guzzi, P. Nadolsky, B. Wang, C.-P. Yuan

April 3, 2013

NNLL Q_T resummation in ResBos

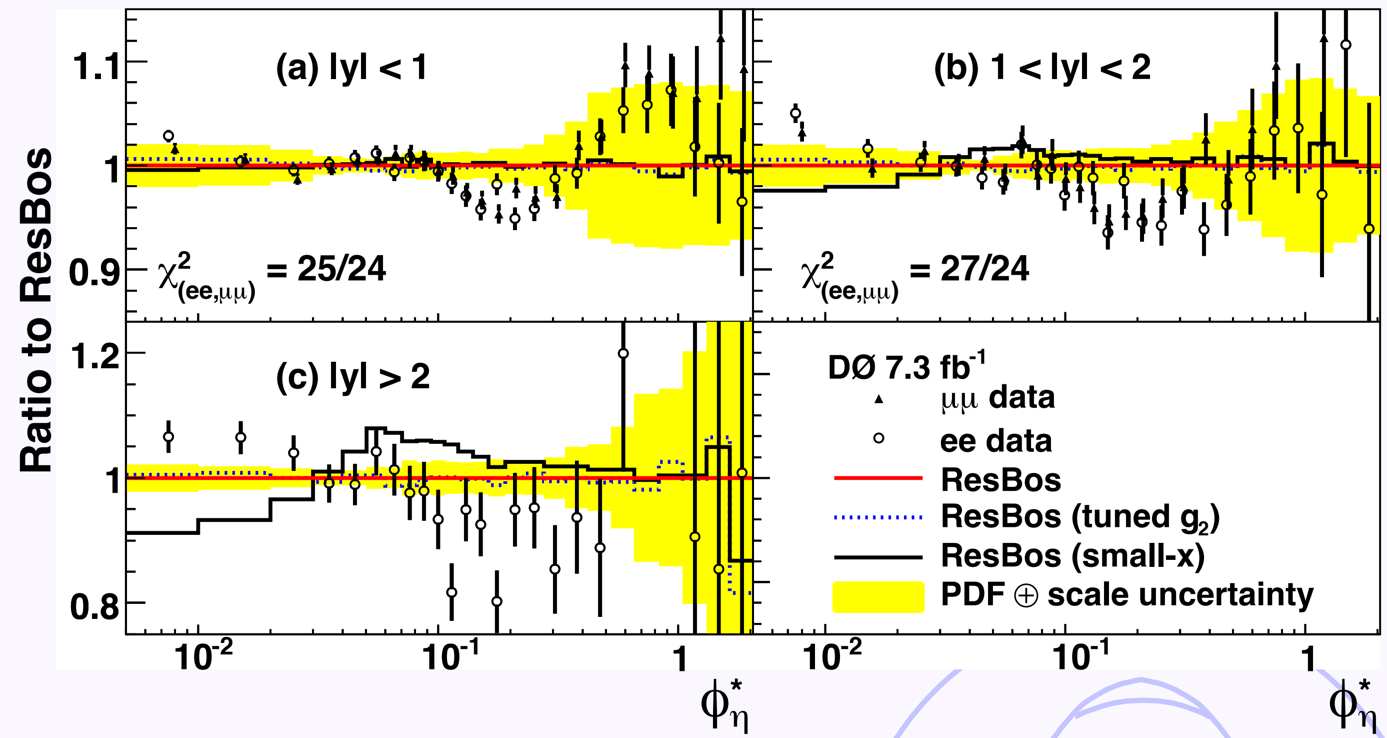
(Balazs, Yuan, 1997; Brock, Landry, Nadolsky, Yuan, 2002)

ResBos is an exact QCD calculation that includes dominant NNLL/NNLO perturbative and nonperturbative contributions.

It typically describes the Q_T and ϕ^*_η data better than other available codes.

The agreement can be further improved both at the Tevatron and LHC by tuning QCD scales and the nonperturbative function

(Guzzi, Nadolsky, Wang, arXiv:1209.1252)



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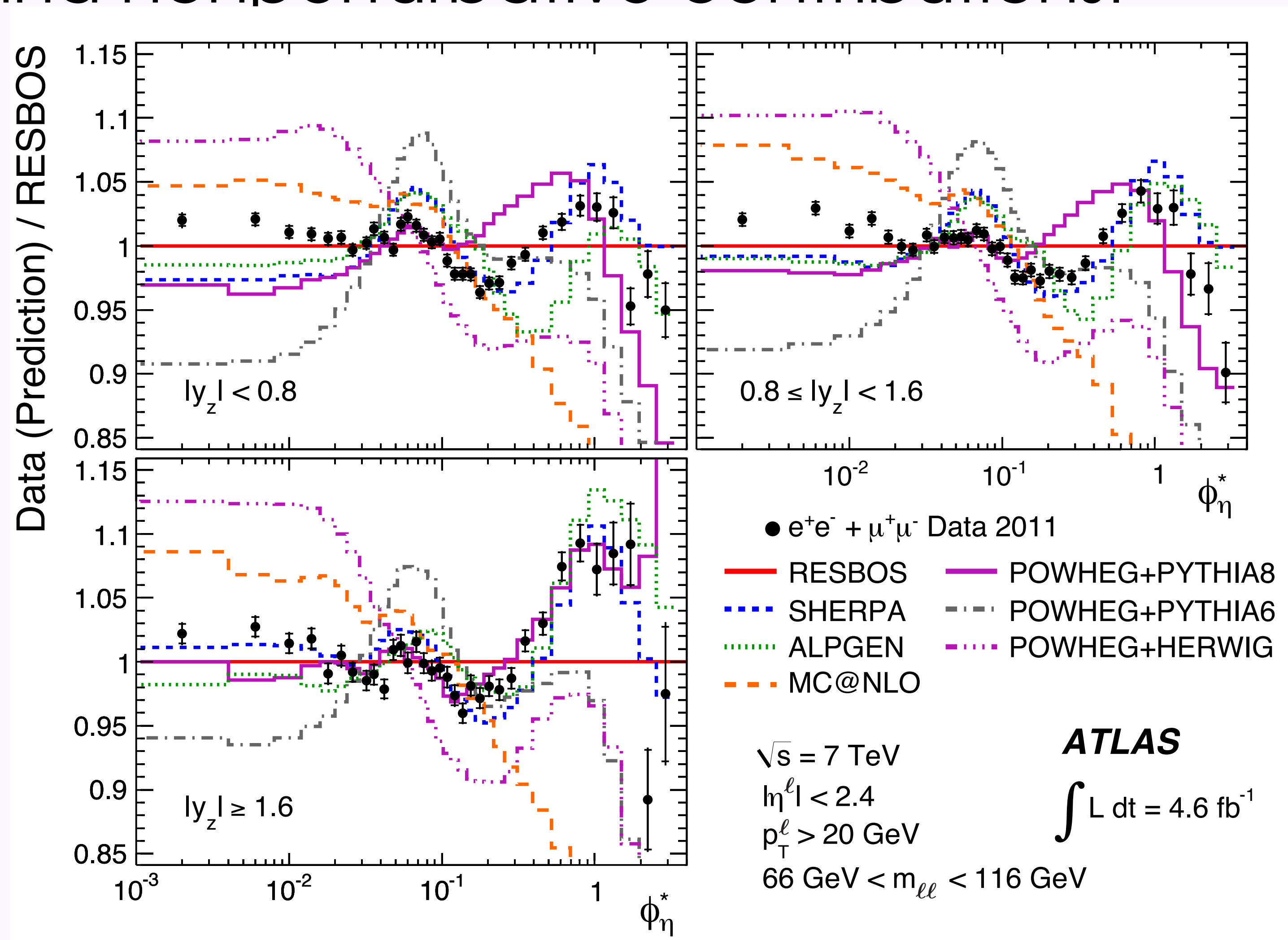


ResBos, 2012 version

★ Close approximation to the full resummed NNLL/NNLO computation at the lepton level

★ Sufficient for describing the current Z data, will continue to advance to include remaining small NNLO terms.

- Small Q_T: Exact coefficients $A^{(3)}, B^{(2)}$; the $\mathcal{C}^{(2)}$ coefficient found numerically using CANDIA *(Guzzi, Cafarella, Corianò 2006)*

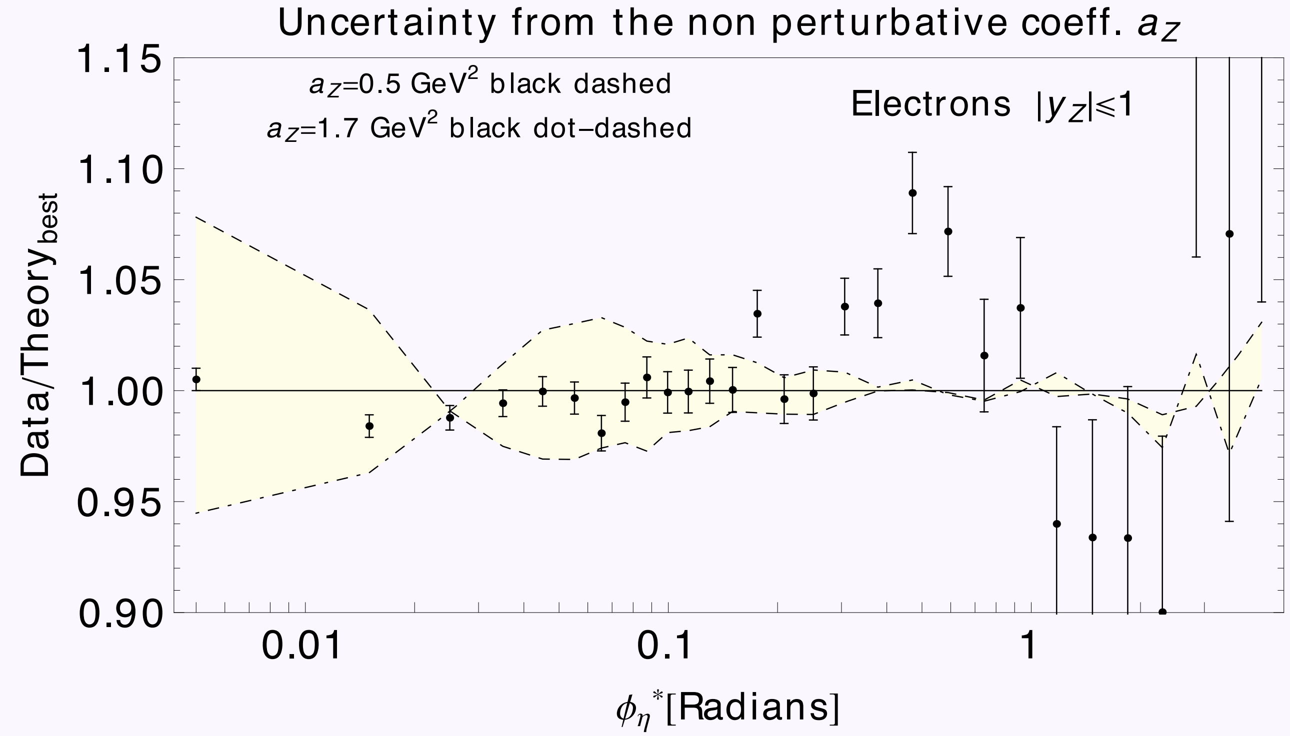
- Large Q_T: The $Y = Y_{NLO} K_{NNLO}$ piece is computed up to $O(\alpha_s^2)$ by *Arnold and Reno Nucl.Phys. B319 (1989); Arnold and Kauffman Nucl.Phys. B349 (1991)*, for the dominant structure function.

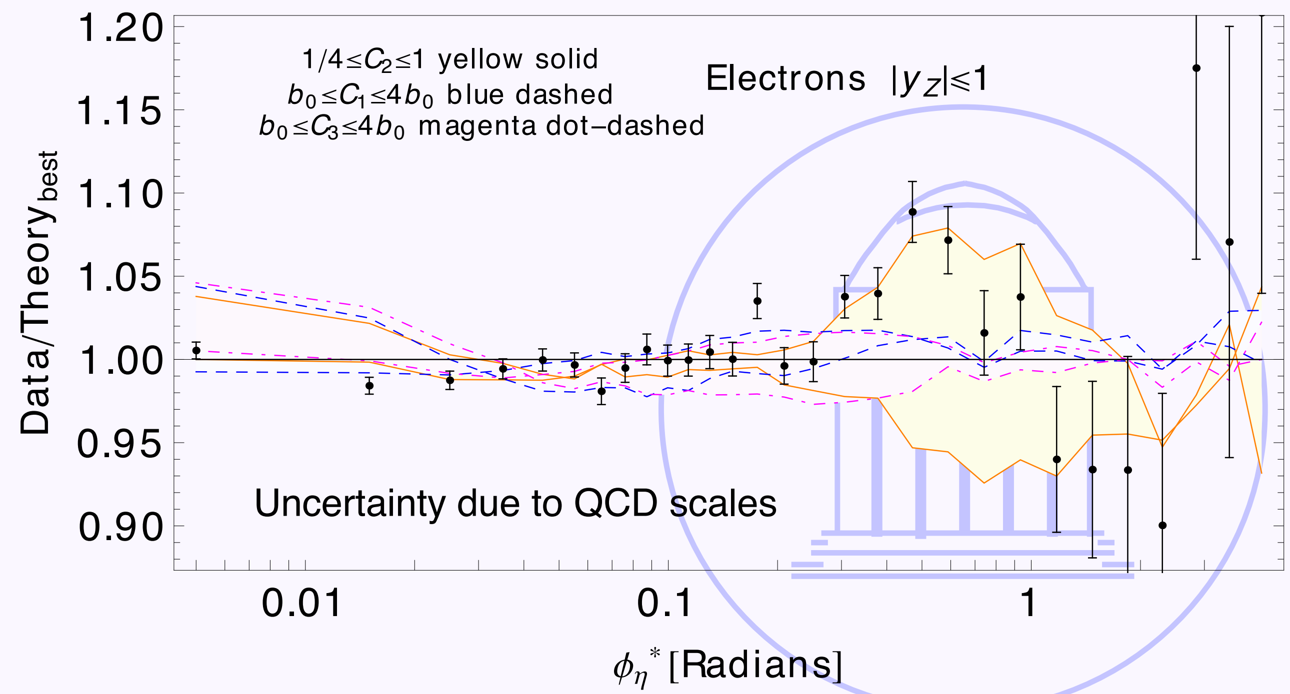
- Complete scale dependence at NNLL/NNLO; reduced scale uncertainty compared to NLL/NLO

Separating dependence on QCD scales and nonperturbative Q_T smearing contributions

With current ResBos precision, dependence on the nonperturbative Gaussian k_T can be discriminated from QCD scale dependence *(arXiv:1209.1252)*

Agreement with Z data requires nonperturbative Gaussian smearing $\mathcal{F}_{NP} \approx a_1 b^2$ with $a_1 \approx 1$ GeV^2, independently of $\sqrt{s}$ or Z rapidity





Data from D0 Run-2, 1010.0262(hep-ex)

Back-up slides

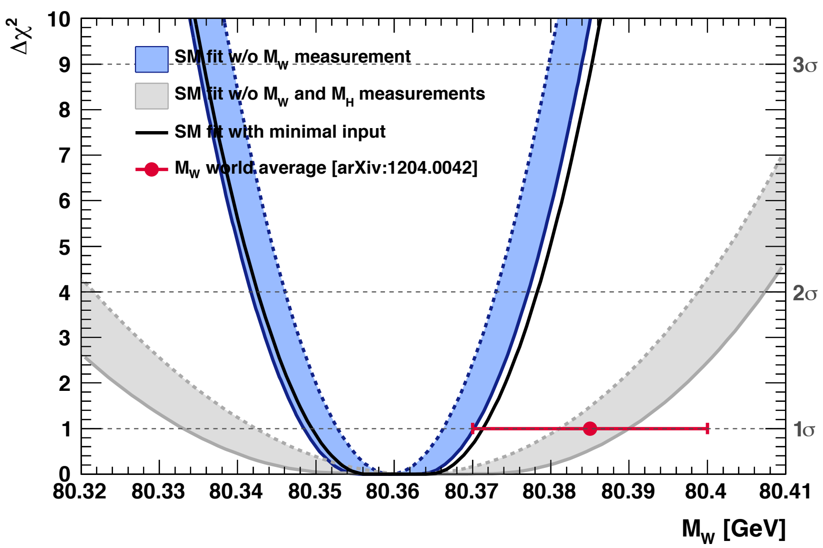
Precision test of the SM model after the Higgs boson discovery

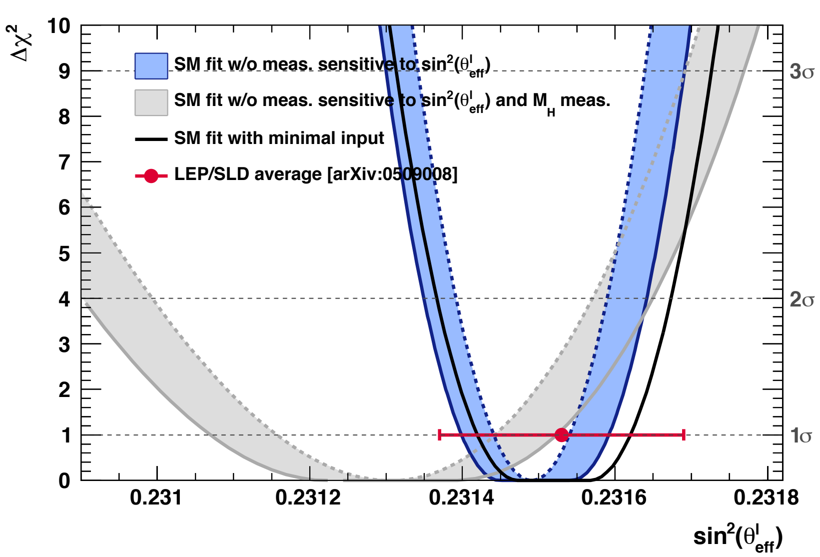
- the SM is fully determined (gauge sector) once (g, g', v, λ) are assigned

  e.g.: using α, G_μ, MZ, MH in input, all the other observables can be predicted

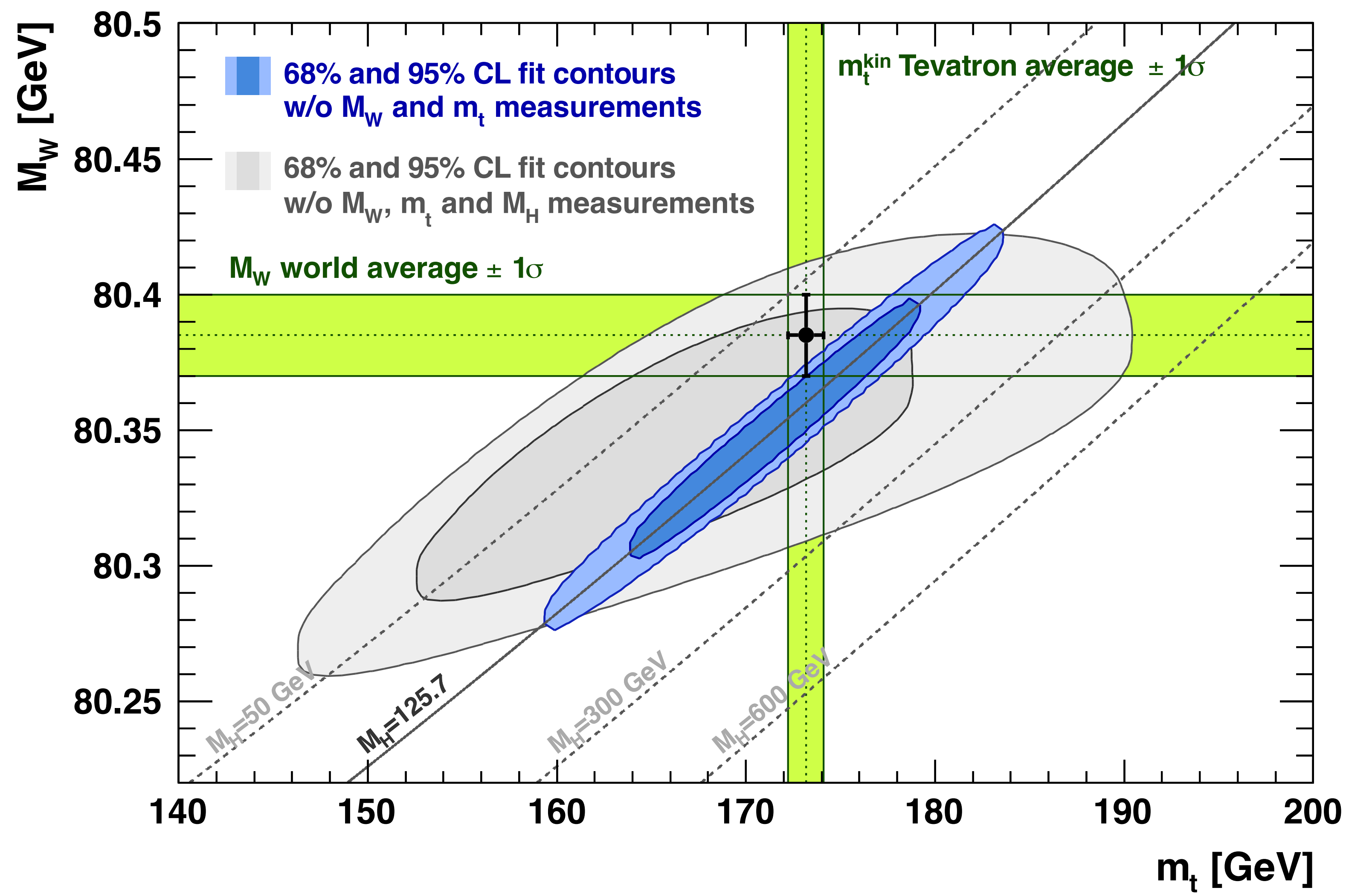
  → a precise measurement of any other observable tests the validity of the SM at the quantum level

  a special role is played by MW and $\sin^2\theta^W$





plots from GFitter group, arXiv:1209.2716



- the extraction of MW is based on templates → is (weakly) model dependent

The POWHEG method (Nason 2004, Frixione Nason Oleari 2007, Alioli Nason Oleari Re 2009)

matching NLO-QCD matrix elements with QCD Parton Shower

- avoiding double counting between the first emission (hard matrix element) and the PS radiation
- generating positive weight events
- independent of the details of the (vetoed) shower adopted

$$d\sigma = \sum_{f_b} \bar{B}^{f_b}(\Phi_n) d\Phi_n \left\{ \Delta^{f_b}\left(\Phi_n, p_T^{min}\right) + \sum_{\alpha_r \in \{\alpha_r | f_b\}} \frac{\left[d\Phi_{rad}\, \theta(k_T - p_T^{min})\, \Delta^{f_b}(\Phi_n, k_T)\, R(\Phi_{n+1}) \right]_{\alpha_r}^{\bar{\Phi}_n^{\alpha_r} = \Phi_n}}{B^{f_b}(\Phi_n)} \right\}$$

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- NLO-(QCD+EW) accuracy of the total cross section: inclusion of virtual corrections,
  integral over the whole phase space of (subtracted) real matrix element

$$\bar{B}^{f_b}(\Phi_n) = \left[B(\Phi_n) + V(\Phi_n) \right]_{f_b} + \sum_{\alpha_r \in \{\alpha_r | f_b\}} \int \left[\theta\left(k_T(\Phi_{n+1}) - p_T\right)\, R(\Phi_{n+1}) \right]_{\alpha_r}^{\bar{\Phi}_n^{\alpha_r} = \Phi_n} d\Phi_{rad}$$

$$+ \sum_{\alpha_\oplus \in \{\alpha_\oplus | f_b\}} \int \frac{dz}{z}\, G_\oplus^{\alpha_\oplus}(\Phi_{n,\oplus}) + \sum_{\alpha_\ominus \in \{\alpha_\ominus | f_b\}} \int \frac{dz}{z}\, G_\ominus^{\alpha_\ominus}(\Phi_{n,\ominus})$$

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$$+ \sum_{\alpha_\oplus \in \{\alpha_\oplus | f_b\}} \int \frac{dz}{z}\, G_\oplus^{\alpha_\oplus}(\Phi_{n,\oplus}) + \sum_{\alpha_\ominus \in \{\alpha_\ominus | f_b\}} \int \frac{dz}{z}\, G_\ominus^{\alpha_\ominus}(\Phi_{n,\ominus})$$

- (N)LO-(QCD+QED) accuracy of the real emission probability: exact real matrix elements,

The POWHEG method (Nason 2004, Frixione Nason Oleari 2007, Alioli Nason Oleari Re 2009)

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- (N)LO-(QCD+QED) accuracy of the real emission probability: exact real matrix elements,
  are used also in the Sudakov form factor (instead of the collinear splitting function)

$$\Delta^{f_b}(\Phi_n, p_T) = \exp\left\{ - \sum_{\alpha_r \in \{\alpha_r | f_b\}} \int \frac{\left[\theta\left(k_T(\Phi_{n+1}) - p_T\right)\ R(\Phi_{n+1}) \right]_{\alpha_r}^{\Phi_n^{\alpha_r} = \Phi_n}}{B^{f_b}(\Phi_n)} d\Phi_{rad} \right\}$$

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  are used also in the Sudakov form factor (instead of the collinear splitting function)

$$\Delta^{f_b}(\Phi_n, p_T) = \exp\left\{ - \sum_{\alpha_r \in \{\alpha_r | f_b\}} \int \frac{\left[\theta\left(k_T(\Phi_{n+1}) - p_T\right)\ R(\Phi_{n+1}) \right]_{\alpha_r}^{\Phi_n^{\alpha_r} = \Phi_n}}{B^{f_b}(\Phi_n)} d\Phi_{rad} \right\}$$

- The curly bracket, integrated over the whole phase space, is equal to 1 :
  the NLO accuracy of the total cross section is preserved

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  integral over the whole phase space of (subtracted) real matrix element

$$\bar{B}^{f_b}(\Phi_n) = \left[B(\Phi_n) + V(\Phi_n) \right]_{f_b} + \sum_{\alpha_r \in \{\alpha_r | f_b\}} \int \left[\theta\left(k_T(\Phi_{n+1}) - p_T\right)\ R(\Phi_{n+1}) \right]_{\alpha_r}^{\bar{\Phi}_n^{\alpha_r} = \Phi_n} d\Phi_{rad}$$
$$+ \sum_{\alpha_\oplus \in \{\alpha_\oplus | f_b\}} \int \frac{dz}{z}\, G_\oplus^{\alpha_\oplus}(\Phi_{n,\oplus}) + \sum_{\alpha_\ominus \in \{\alpha_\ominus | f_b\}} \int \frac{dz}{z}\, G_\ominus^{\alpha_\ominus}(\Phi_{n,\ominus})$$

- (N)LO-(QCD+QED) accuracy of the real emission probability: exact real matrix elements,
  are used also in the Sudakov form factor (instead of the collinear splitting function)

$$\Delta^{f_b}(\Phi_n, p_T) = \exp\left\{ - \sum_{\alpha_r \in \{\alpha_r | f_b\}} \int \frac{\left[\theta\left(k_T(\Phi_{n+1}) - p_T\right)\ R(\Phi_{n+1}) \right]_{\alpha_r}^{\Phi_n^{\alpha_r} = \Phi_n}}{B^{f_b}(\Phi_n)} d\Phi_{rad} \right\}$$

- The curly bracket, integrated over the whole phase space, is equal to 1 :
  the NLO accuracy of the total cross section is preserved

- The POWHEG (first) emission is by construction the hardest:
  HERWIG/PYTHIA are bound to radiate partons with lower virtuality (transverse momentum)

Inclusion in POWHEG of the exact O(α) EW corrections

$$d\sigma = \sum_{f_b} \bar{B}^{f_b}(\Phi_n) d\Phi_n \left\{ \Delta^{f_b}\left(\Phi_n, p_T^{min}\right) + \sum_{\alpha_r \in \{\alpha_r | f_b\}} \frac{\left[d\Phi_{rad}\ \theta(k_T - p_T^{min})\ \Delta^{f_b}(\Phi_n, k_T)\ R(\Phi_{n+1}) \right]_{\alpha_r}^{\bar{\Phi}_n^{\alpha_r} = \Phi_n}}{B^{f_b}(\Phi_n)} \right\}$$

- the final state may contain 0 or 1 additional partons
  the parton can be 1 gluon or 1 photon (qqbar subprocess) or 1 quark (qg subprocess)

- the virtuality (transverse momentum) of the emitted parton sets the largest virtuality that the Parton Shower can reach

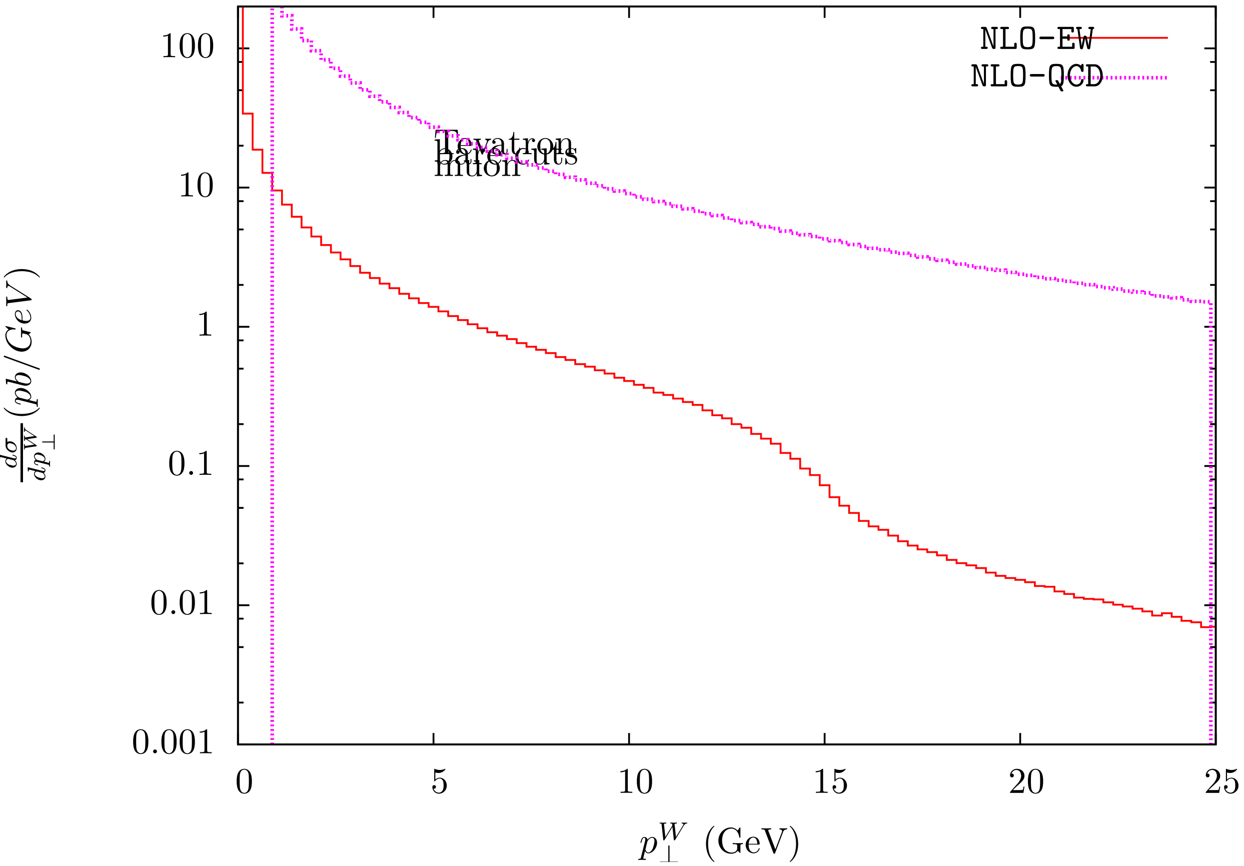
- the Parton Shower can be a pure QCD shower (BW) or a mixed QCD/QED shower (BMNNP(V))

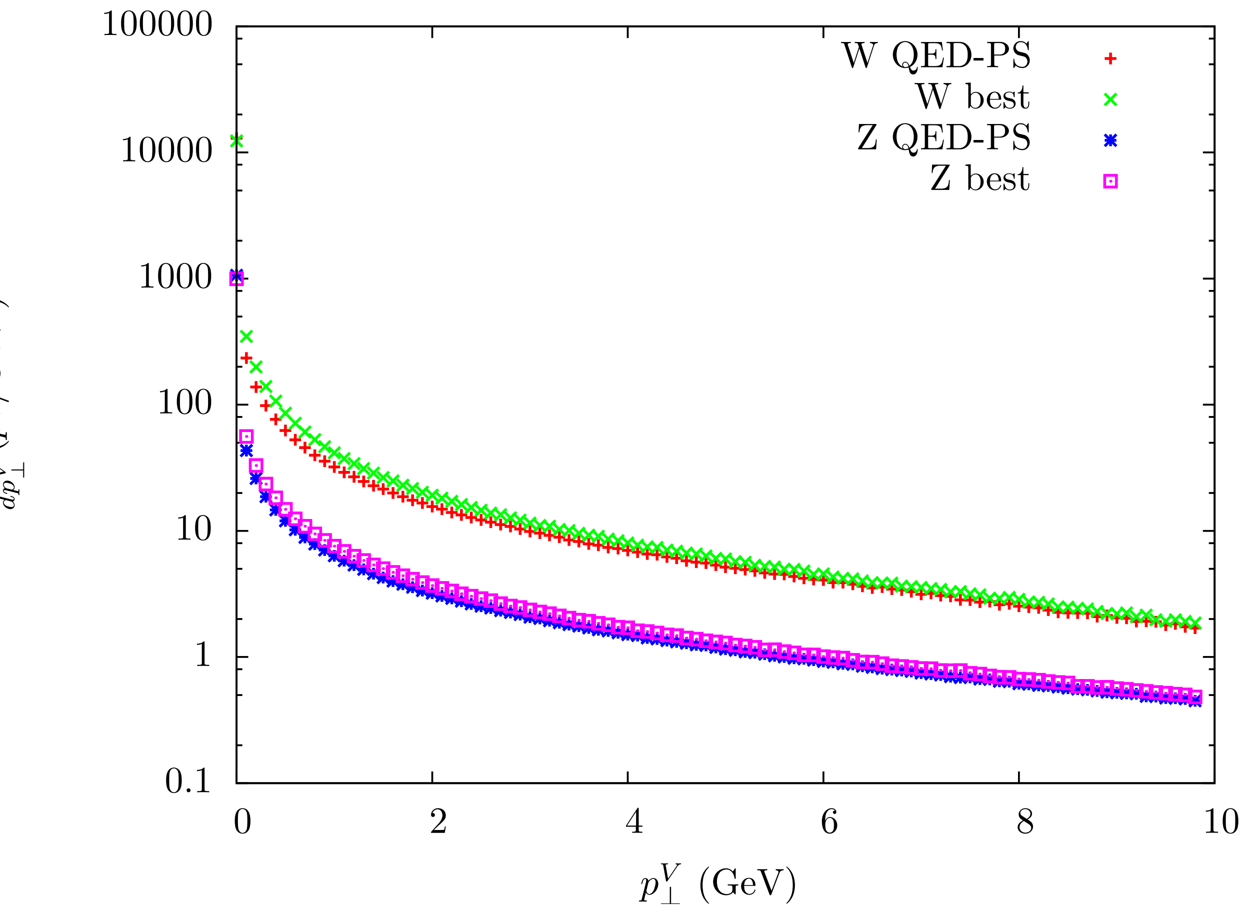
- the process has three regions of collinear singularity, associated to the emission of
  one final state photon, one initial state photon, one initial state gluon/quark
  the Sudakov form factor is given by the product of the three individual form factors, for the three regions of collinearity

- the soft/collinear divergences have been regularized
  by phase-space slicing and final state lepton masses (BW) or
  in a mixed scheme using dimensional regularization to treat the quark and photon singularities
  and the lepton mass as natural cut-off of the final state mass singularities (BMNNP(V))

- the virtual corrections have been implemented according to the WGRAD results (BW)
  or reproducing independently the HORACE results (BMNNP(V)) with the option of working in the complex mass scheme

QED induced W(Z) transverse momentum





The uncertainty on ptW directly translates into an uncertainty on the final MW value.

Photon radiation yields a tiny gauge boson transverse momentum.

This momentum is different in the CC and NC channels because of the different flavor structure.

A possible estimate of the "non-final state" component differs in the 2 cases by 54 (Z) - 33 (W) = 21 MeV

$\langle p_\perp^V \rangle =$

Z FSR-PS	0.409	GeV
Z best	0.463	GeV
W FSR-PS	0.174	GeV
W best	0.207	GeV

The fit of the non perturbative QCD parameters is done on the Z transverse momentum and it is necessary to properly remove the EW corrections to the NC channel

In the simulation of the CC channel the relevant EW corrections are then applied

Matching NLO calculations with resummation: DYqT

Bozzi, Catani, De Florian, Ferrera, Grazzini

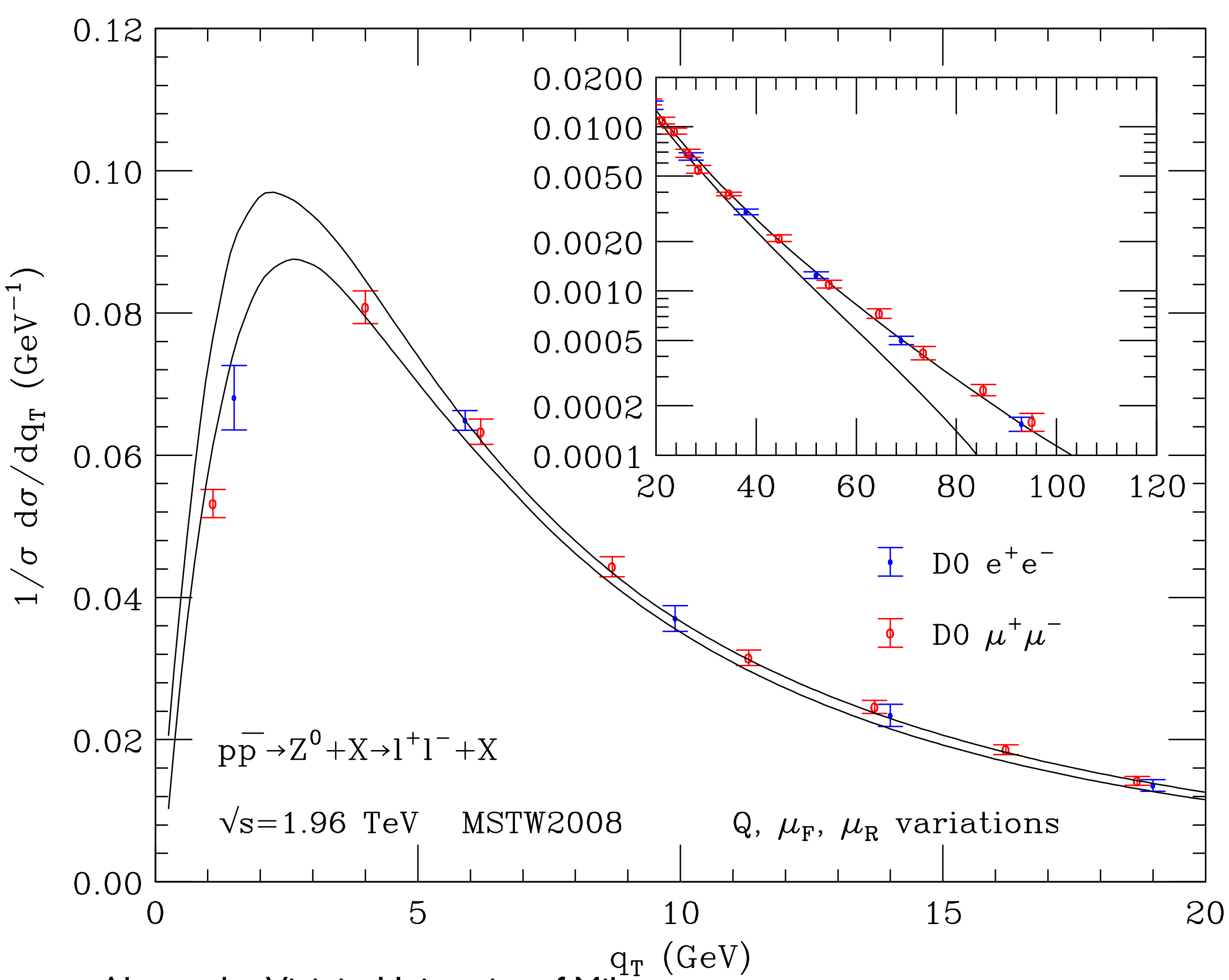
$$\frac{d\hat{\sigma}^{(\mathrm{res.})}_{V\,ab}}{dq_T^2}(q_T, M, \hat{s}; \alpha_S(\mu_R^2), \mu_R^2, \mu_F^2) = \frac{M^2}{\hat{s}} \int_0^\infty db\, \frac{b}{2}\, J_0(bq_T)\, \mathcal{W}^V_{ab}(b, M, \hat{s}; \alpha_S(\mu_R^2), \mu_R^2, \mu_F^2)\ ,$$

process dependent

$$\mathcal{W}^V_N(b, M; \alpha_S(\mu_R^2), \mu_R^2, \mu_F^2) = \mathcal{H}^V_N\left(M, \alpha_S(\mu_R^2); M^2/\mu_R^2, M^2/\mu_F^2, M^2/Q^2\right) \times \exp\{\mathcal{G}_N(\alpha_S(\mu_R^2), L; M^2/\mu_R^2, M^2/Q^2)\}\ ,$$

universal

G. Bozzi, S.Catani, D. de Florian, G. Ferrera, M. Grazzini , arXiv:1007.2351



Q is the resummation scale

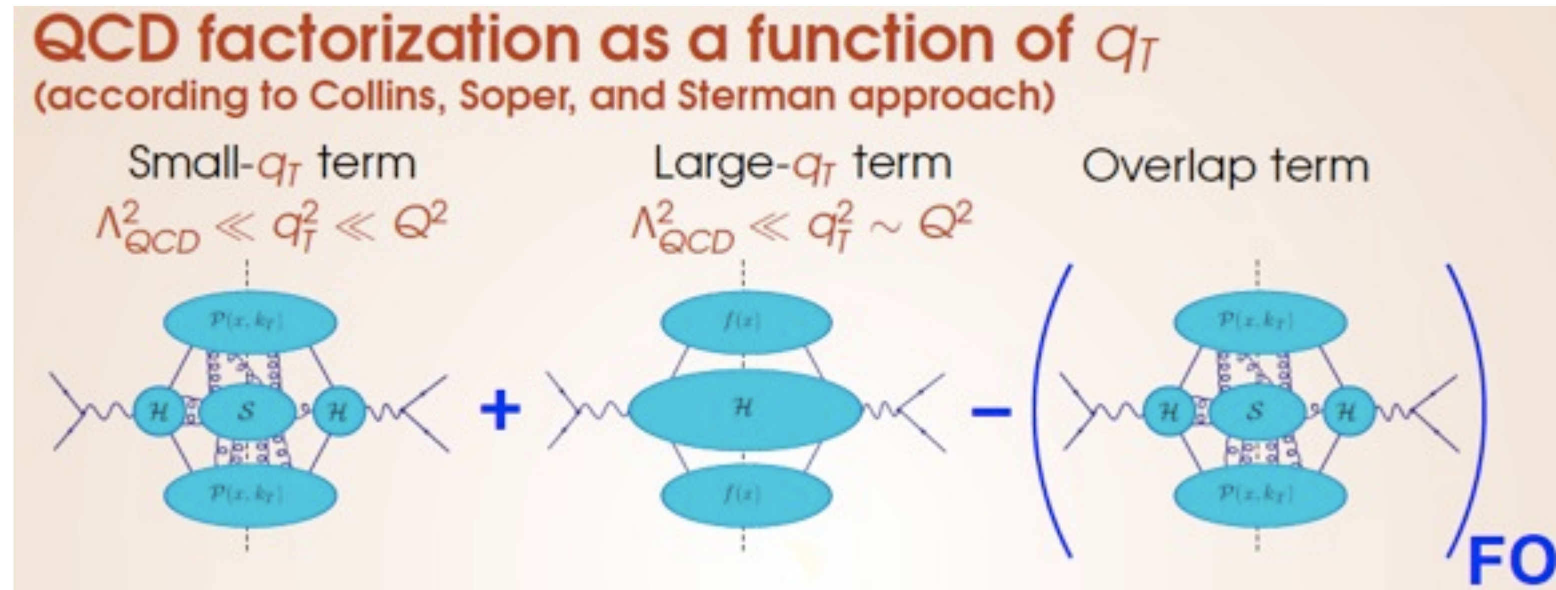
the fixed order total cross section is by construction reproduced

a non-perturbative smearing factor can be applied on top of the pQCD result

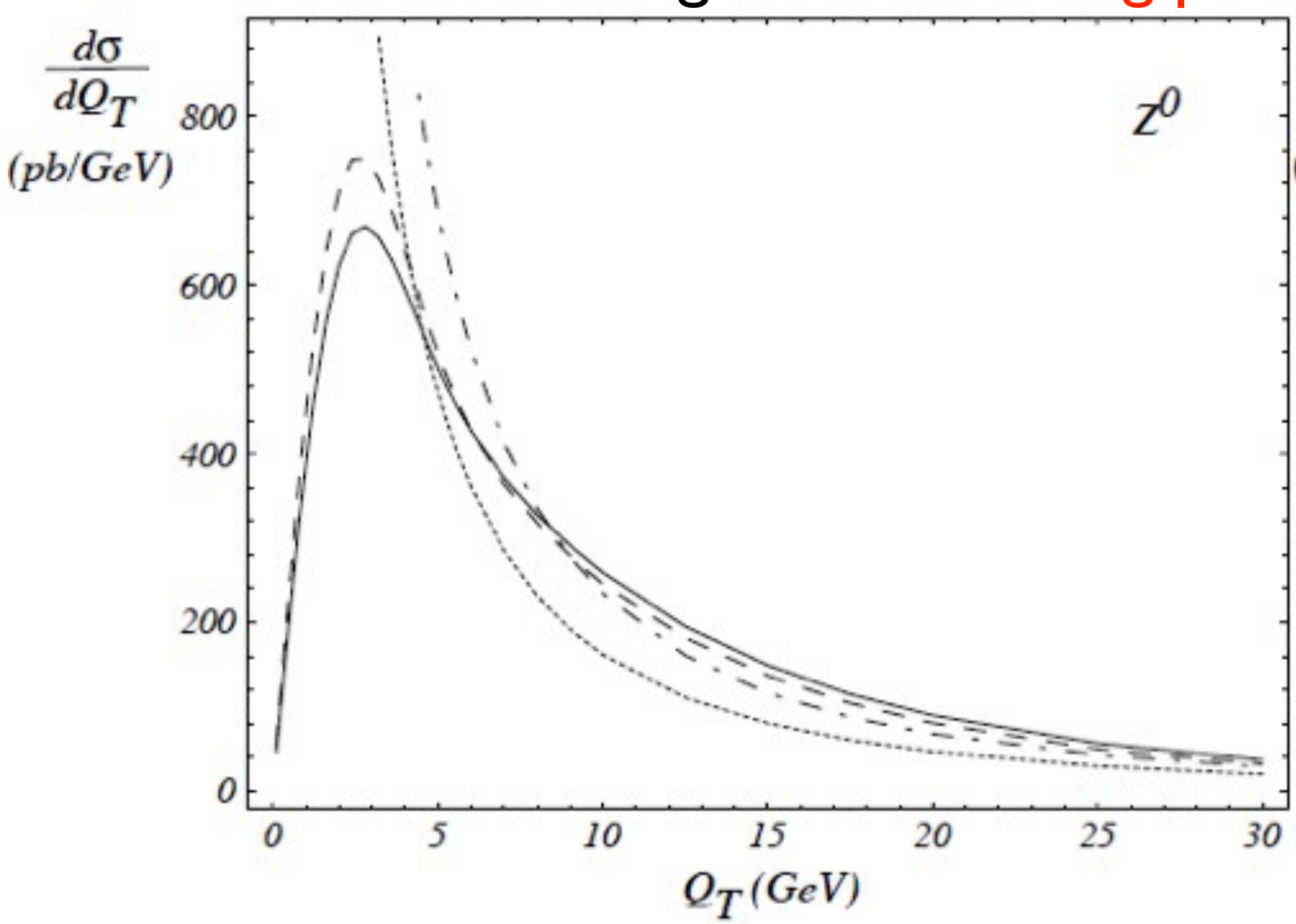
Matching NLO calculations with resummation: ResBos

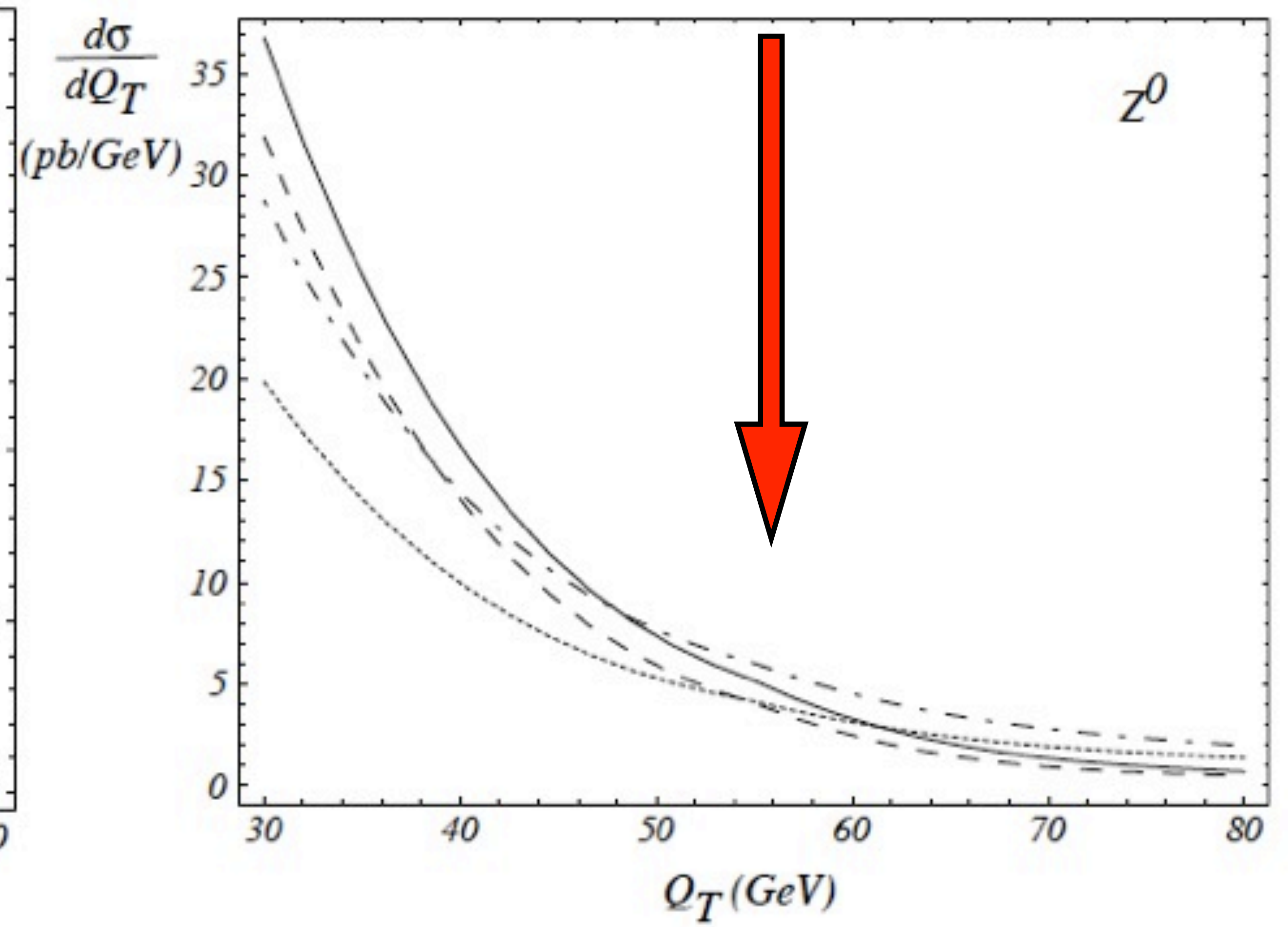
Landry, Brock, Nadolski, Yuan, Balazs

- Finite order: part of the NNLO results
  lepton spin correlation at NLO
- Resummed term *W* at NNLL
  for Sudakov factor and non-collinear *pdfs*
- Two representations of the
  hard-vertex function *H*



matching at the crossing point between resummed and fixed order results





Comparison between POWHEG and MC@NLO

$$d\sigma^{\mathrm{NLO+PS}} = d\Phi_B \bar{B}^s(\Phi_B) \left[\Delta^s(p_\perp^{\mathrm{min}}) + d\Phi_{R|B} \frac{R^s(\Phi_R)}{B(\Phi_B)} \Delta^s(p_{\mathrm{T}}(\Phi)) \right] + d\Phi_R R^f(\Phi_R)$$

$$\bar{B}^s = B(\Phi_B) + \left[V(\Phi_B) + \int d\Phi_{R|B} R^s(\Phi_{R|B}) \right]$$

R^s enters in the Sudakov form factor $\Delta^s(p_T(\Phi))$

the virtuality of the first, hardest emission is analogous to the resummation scale in DYqT, different event by event

MC@NLO

$$R^s \propto \frac{\alpha_s}{t} P_{ij}(z) B(\Phi_B)$$

$$R^f = R - R^s$$

the universal collinear splitting function is used in the Sudakov

the full matrix element R is used only in the regular part

POWHEG

$$R^s = \frac{h^2}{h^2 + p_{\mathrm{T}}^2} R\,, \qquad R^f = \frac{p_{\mathrm{T}}^2}{h^2 + p_{\mathrm{T}}^2} R$$

the scale *h* (introduced in the Higgs gluon fusion code) divides low from large ptH values

at low ptH, R tends to its collinear approximation
at large ptH the damping factor suppresses R in the Sudakov

- the two approaches exactly agree at NLO-QCD, they differ by higher order corrections

a choice of *h* that mimics a NLO+NNLL shape must be supplemented by a study on the systematics obtained by varying *h*

different choices for Rf, combined with the cross section unitarity constraint, may lead to an uncertainty band on ptH